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INSTITUTE FOR DEFENSE ANALYSES

Development of the Morphing Capability Assessment Tool

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PREFACE

This study was conducted under the “Morphing Capability Assessment Process” task as part of the Institute for Defense Analyses (IDA) Central Research Program (CRP).

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EXECUTIVE SUMMARY

Morphing technologies and vehicles are of interest to many people, including scientists and engineers from many disciplines and many nontechnical professionals. As morphing research and development (R&D) continues, ideas, concepts, and information have to be communicated effectively and to R&D efforts have to be coordinated. Effective communication and coordinated R&D efforts within and across varied organizations means that information must be conveyed so that many people can readily and clearly understand the information and its impact. This need to communicate and to coordinate R&D efforts motivated the development of a morphing capability assessment framework.

The morphing capability assessment framework presented in this report is a starting point to aid effective communication and to coordinate R&D efforts for morphing vehicles and morphing vehicle technologies. The framework attempts to establish a logical process to answer questions such as "Why is a morphing vehicle better than a conventional vehicle for a desired mission or set of missions?" and "What technologies are needed to realize a proposed morphing vehicle?" Starting with the definition of morphing, a capability assessment process that systematically considers the desired vehicle performance, the technologies and risks associated with achieving the desired performance through morphing, and a method to map progress toward more capable morphing vehicles are discussed. To facilitate an understanding of the proposed process, an example based on two aircraft—one that has advanced morphing capabilities and one that does not—is fully worked.

In addition, a panel discussion was held at the 12th AIAA/ASME/AHS Adaptive Structures Conference, in conjunction with the 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (Palm Springs, California, in April 2004), where the conference paper describing the proposed tool was presented and discussed with members of the aerospace community. The impressions and suggestions of the attendees are captured in this document, along with explanations and possible solutions to address their concerns and improve the Morphing Capability Assessment (MCA) tool.

I. INTRODUCTION

A. BACKGROUND OF THE MORPHING AIRCRAFT CONCEPT

Traditional military aircraft designs, even those intended as multimission platforms, produce aircraft that are performance optimized for only a narrow segment of the flight envelope. Consequently, military aircraft have often been designed predominantly for one mission (e.g., air-to-air combat, long-range bombing, or equipment transport). Because of this narrow design focus, significant performance penalties are paid for mission phases that require flight outside the optimized flight envelope. Advances in the field of smart materials and structures, combined with evolving operational needs, have motivated science and technology (S&T) program managers (PMs) and researchers to consider the development of aircraft capable of efficiently performing multiple missions based on morphing capabilities. Such aircraft could provide the warfighter a smaller number of highly flexible multimission platforms capable of high performance across a broad flight envelope.

From 1990 through 2000, structures capable of limited adaptation to operational and environmental conditions were demonstrated. These adaptable structures—aircraft wings and engine inlets (Ref. 1)—used advances in the field of smart materials and structures (including integrated sensors, actuators, and controllers) to achieve limited shape change. The smart materials and structures community recognized that these demonstrations had just "scratched the surface" of the full potential of adaptable or smart systems capabilities. To continue development toward this perceived full potential, the idea of morphing was proposed. For air vehicles, morphing was initially defined as a significant vehicle shape change.

Dr. Rich Wlezien [National Aeronautics and Space Administration (NASA)-Langley][1] initiated the NASA Morphing Program to develop innovative technologies to achieve such shape changes. After the NASA Morphing Program was begun, Dr. Ephrahim Garcia[2] of the Defense Advanced Research Projects Agency/Defense

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1 Dr. Wlezien is now at NASA Headquarters as Director of the Vehicle System Program.

2 Dr. Garcia is now an Associate Professor at Cornell University.

Sciences Office (DARPA/DSO) undertook planning for a new program to develop adaptive military air and space platforms that have radically new mission capabilities based on the ability of the platform to change shape significantly or to morph. The result of these planning efforts was the DARPA/DSO Morphing Air Structures (MAS) Program, which is currently under the management of Dr. Terry Weisshaar. In addition to the establishment of these programs, the concept of morphing evolved beyond considering shape change as the only way a vehicle could adapt to operational and environmental conditions to provide radically new mission capabilities.

S&T efforts in the Armed Services and at NASA were revitalized by these new ideas and programs. To capitalize further on these developments, the Office of Naval Research (ONR) and DARPA/DSO co-sponsored an In-Flight Reconfigurable Aircraft (IFRA) Workshop in December 2002 (Ref. 2). The workshop brought together a multidisciplinary team of government, university, and industry specialists to

- Establish a common vision and understanding of how morphing might benefit future military air vehicle capabilities
- Identify critical path technologies and analytical tools to achieve such new capabilities
- Draft a technology/tool maturation timeline with rough order-of-magnitude costs to achieve such new capabilities
- Determine potential areas for coordination and for leveraging of S&T investments based on current efforts and technology readiness levels (TRLs).

The workshop focused solely on vehicle shape change for fixed-wing air vehicles operating up to high subsonic flight conditions.

To achieve the workshop objectives, a clear and consistent definition of morphing was required. While many definitions of morphing are in use today, for the workshop and in this report, morphing is defined as a capability to provide superior and/or new vehicle system performance by tailoring the vehicle's state to adapt to the environment and multivariable mission roles, where

- Performance includes agility/maneuverability, range, speed, acceleration, radar cross section (RCS), payload/weapons and sensors, and so forth
- Vehicle state includes physical geometry/configuration, mechanical properties, electromagnetic properties, and so forth

- Environment includes operational conditions, both natural and threat-based, such as temperature, humidity, shock, vibration, electromagnetic, and so forth.

B. INCEPTION AND GOAL OF THE MORPHING CAPABILITY ASSESSMENT (MCA) PROCESS

During IFRA workshop planning, needs for metrics, a method to assess morphing capabilities, and a means to represent the assessment information were identified. Initial MCA method development efforts were based, in part, on the Air Force's approach to develop autonomous unmanned aerial vehicle (UAV) control intelligence metrics (Ref. 3). The intent of these efforts was to develop a framework to assess morphing capabilities to aid in program planning and in tracking advancement of morphing research and development (R&D) projects. The work presented in this report is the result of these efforts and was supported, in part, through the Central Research Program (CRP) at the Institute for Defense Analyses (IDA).

The establishment of a general morphing capability assessment method is a long-term goal. This effort is an initial step. As morphing vehicle and related technology R&D efforts continue, there will be a need to exchange ideas and information effectively and to coordinate efforts within the S&T community across several organizations. These needs motivated the development of a MCA framework, efforts of which are reported here.

Currently, many approaches are used to convey the potential effect of developing morphing aircraft and technologies for mission capabilities. Consequently, comparing and contrasting morphing vehicle and technology programs is challenging. Moreover, morphing capability should not be limited to air vehicles. Conceptually, vehicles that operate in any environment (air, land, water, space) or any combination of these environments can morph to achieve desired vehicle attributes or states. As the types of potential morphing vehicles and perceived required technologies increase, assessing the impact of morphing on capabilities and identifying technical needs will become more difficult.

This report applies the proposed MCA tool to air vehicles since most current morphing efforts are focused on these vehicles. However, keeping in mind the morphing definition, the proposed framework is general enough to address vehicles operating in different media. The MCA process systematically considers the vehicle's ability to complete a desired mission effectively (based on changes in vehicle performance) and provides a means to assess the technology advancements that enable one or more vehicle components to change the vehicle's state and lead to the desired performance changes.

II. THE MCA PROCESS AND ITS EVOLUTION

At the behest of Mr. Lawrence Ash of ONR, Dr. Carlos Cesnik of the University of Michigan developed an initial Morphing Capability Level (MCL) formulation. The purpose of the tool was to help to establish a common understanding and framework for a discussion of morphing among experts from different disciplines. At the same time, the proposed MCL tool would provide a road-mapping function for morphing vehicle development and act as a means to track progress of this development.

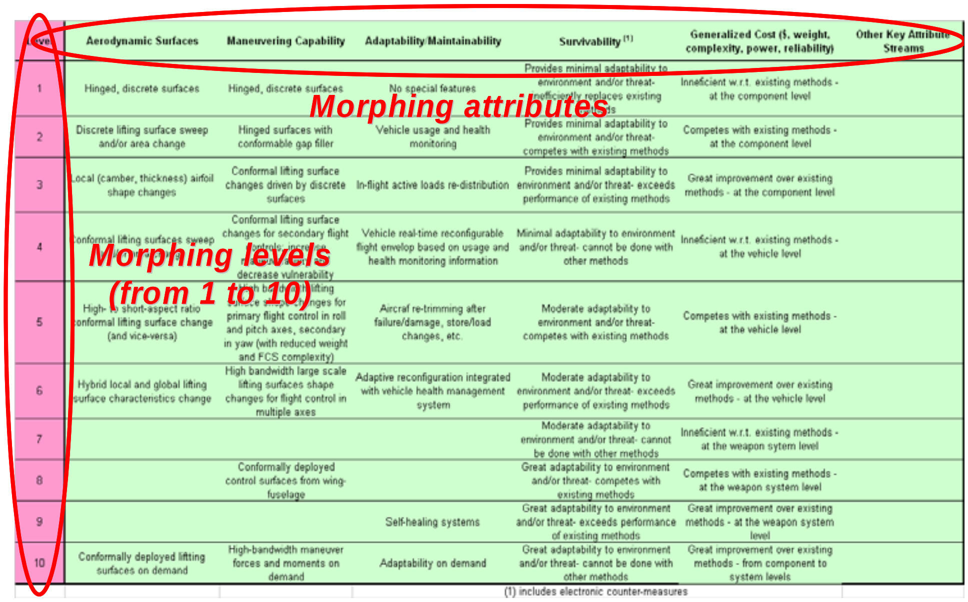
The initial MCL tool consisted of three primary elements:

1. A table to track morphing capability level in a way similar to TRLs
2. A radar plot that summarized the state changes realized through morphing and their effect on important performance parameters, including cost and survivability
3. A scale to assess of the overall mission impact relative to conventional aircraft.

Figure II-1 shows the original MCL table. Figure II-2 shows the mission impact levels and morphing impact on performance (represented by a radar plot). Figure II-3 shows the 3-axis plot that summarizes the overall morphing capability and its impact on the ability to accomplish the (new) missions (as defined in the table in Figure II-2) and in vehicle performance. Because the original application identified for morphing was aircraft, the initial formulation was done using aircraft-specific performance metrics. Then, as morphing technologies were developed for other types of vehicles (e.g., ships and ground vehicles), MCL tables and radar plots would also be developed to cover these vehicles.

A. MODIFICATIONS/REFINEMENTS TO THE INITIAL MCL THAT DID NOT WORK

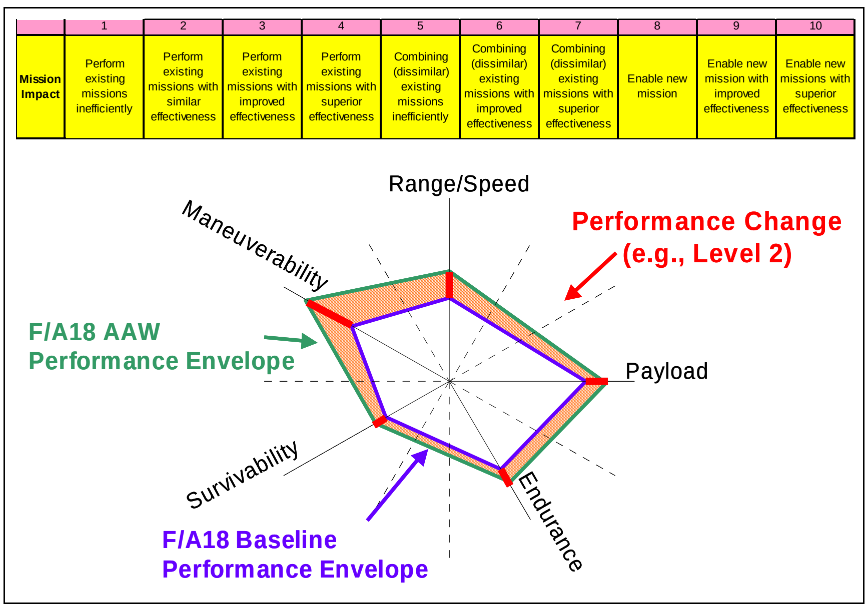
Using the original process as a starting point, changes were made to improve its utility to researchers. Developing the MCL table and determining mission impact were among the difficulties in using the original MCL tool. Specifically, the table’s columns



Level	Aerodynamic Surfaces	Maneuvering Capability	Adaptability/Maintainability	Survivability [1]	Generalized Cost ($, weight, complexity, power, reliability)	Other Key Attribute Streams
1	Hinged, discrete surfaces	Hinged, discrete surfaces	No special features	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	
2	Discrete lifting surface sweep and/or area change	Hinged surfaces with conformable gap filler	Vehicle usage and health monitoring	Provides minimal adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the component level	
3	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes driven by discrete surfaces	In-flight active loads re-distribution	Provides minimal adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the component level	
4	Conformal lifting surfaces sweep [illegible]	Conformal lifting surface changes for secondary flight controls; increase [illegible] decrease vulnerability	Vehicle real-time reconfigurable flight envelop based on usage and health monitoring information	Minimal adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the vehicle level	
5	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw (with reduced weight and FCS complexity)	Aircraf re-trimming after failure/damage, store/load changes, etc.	Moderate adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the vehicle level	
6	Hybrid local and global lifting surface characteristics change	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Adaptive reconfiguration integrated with vehicle health management system	Moderate adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	
7				Moderate adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon sytem level	
8		Conformally deployed control surfaces from wing-fuselage		Great adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the weapon system level	
9			Self-healing systems	Great adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level	
10	Conformally deployed lifting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability on demand	Great adaptability to environment and/or threat- cannot be done with other methods	Great improvement over existing methods - from component to system levels	

(1) includes electronic counter-measures

Figure II-1. Initial MCLTable



	1	2	3	4	5	6	7	8	9	10
Mission Impact	Perform existing missions inefficiently	Perform existing missions with similar effectiveness	Perform existing missions with improved effectiveness	Perform existing missions with superior effectiveness	Combining (dissimilar) existing missions inefficiently	Combining (dissimilar) existing missions with improved effectiveness	Combining (dissimilar) existing missions with superior effectiveness	Enable new mission	Enable new mission with improved effectiveness	Enable new missions with superior effectiveness

Figure II-2. Mission Impact Level (Top) and Morphing Impact on Performance (Represented by the Radar Plot)

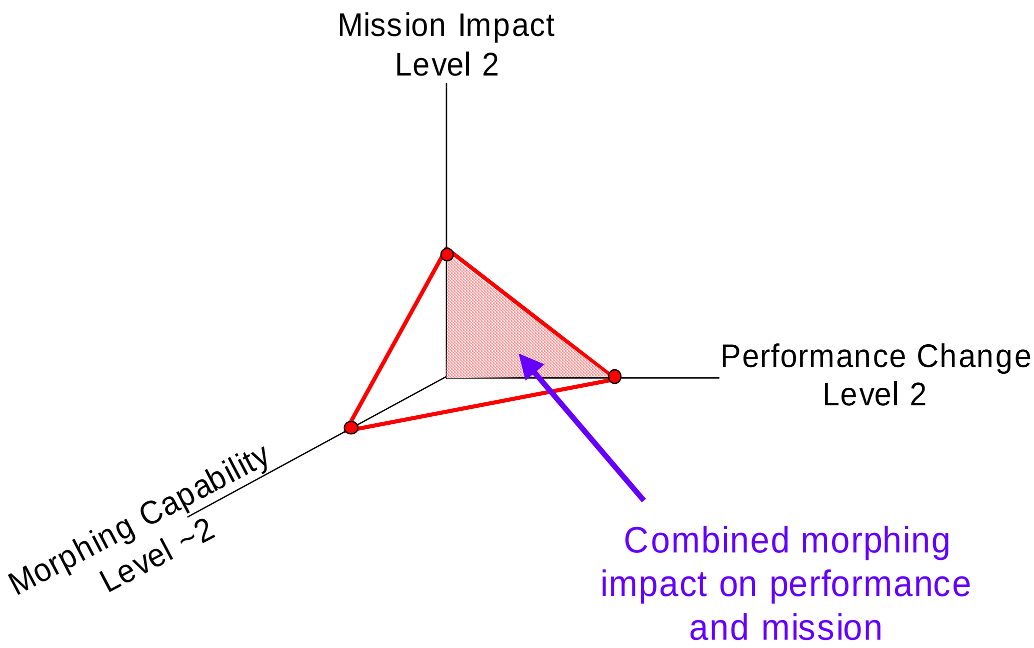


Figure II-3. MCL Combined Performance Graph

and rows were difficult to make overarching and general enough to cover all the possible morphing configurations. Also, the initial table depended heavily on qualitative analysis of the morphing vehicle. Considering how the tool was to be used, a decision was made to investigate a way to make the MCL more quantitative while still maintaining the original goal of a tool to provide a common framework and understanding for morphing.

Building on the final three-dimensional (3-D) plot of the original MCL formulation, methods to generate the morphing levels in more quantitative fashion were considered. Using the information to make the spider plots from the original MCL, a value of 1 to 5 was assigned for performance change, mission capability, and state change. These were then plotted on the 3-axis plot, and the relative morphing capability was inferred. Figure II-4 provides a graphical overview of this modified MCL process. While this approach solved some of the issues associated with the original MCL tool, it still did not completely address the issue of a quantitative assessment of the morphing capability.

A third iteration of the MCL took a much more quantitative approach to the assessment of morphing. This approach combines the spider plots from the first two MCL frameworks with quality function deployment (QFD) analysis to try to arrive at a number that would express the morphing capability of the vehicle.

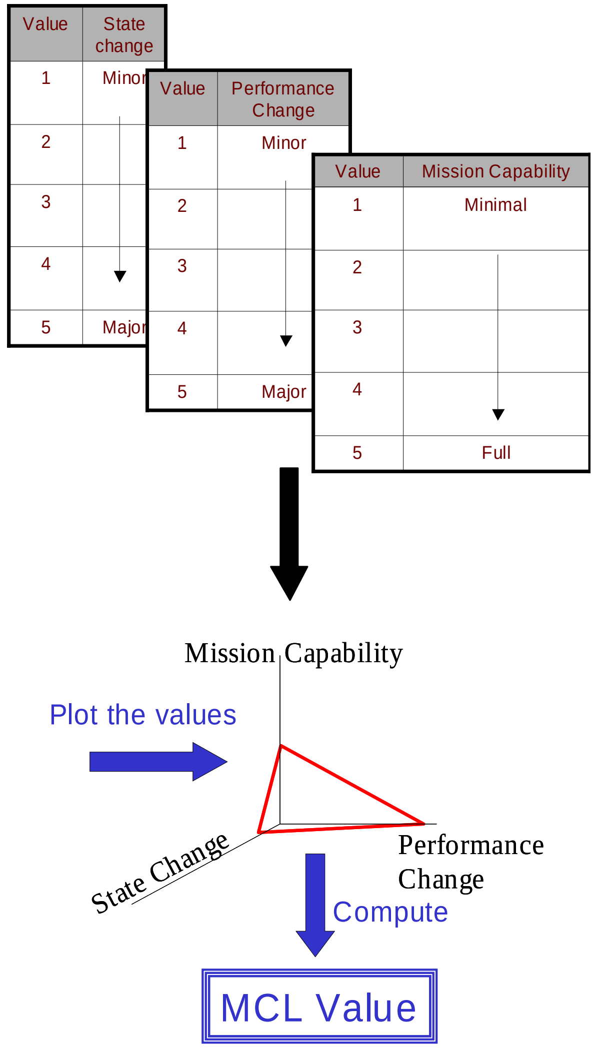


Figure II-4. Outline of the Process Developed for the Second Iteration of the MCL Tool

Beginning with the desired vehicle performance, ratios of the preliminary performance expectations to the desired performance expectations were made (see Figure II-5). The results of each performance ratio were averaged, and that value was assigned as the Mission Impact Score (MIS). The next step used QFD to link the morphing performance gains to the technologies required to achieve the morphing and to the risks associated with these technologies. In the initial QFD formulation, the risk values were counted as negative values, and the technologies were implemented as positive values. These were then summed. This sum total was the Morphing Capability Score (MCS), which, along with the MIS, was used to calculate the MCL. The goal was

F-111

	Morphing Importance	Morphing Changes					Materials and Technologies		Performance Gains				Risks			
		Sweep	Telescoping	Folding	Hingeless Control Surfaces	Other Mechanisms	Smart Materials	Smart Actuators	Manuevering	Speed	Range	Survivability	Cost	Complexity	Manufacturing	
Span	3	4	0	0	0	0	1	1	1	0	0	1	1	1	1	
AR	3	4	0	0	0	0	1	1	1	0	0	1	1	1	1	
Λ	5	9	0	0	0	0	1	1	0	4	1	4	4	4	4	
λ	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
t/c	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
camber	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
		69	0	0	0	0	11	11	6	20	5	26	-26	-26	-26	70
																Morphing Capability Score

F-111 MAW

	Morphing Importance	Morphing Changes					Materials and Technologies		Performance Gains				Risks			
		Sweep	Telescoping	Folding	Hingeless Control Surfaces	Other Mechanisms	Smart Materials	Smart Actuators	Manuevering	Speed	Range	Survivability	Cost	Complexity	Manufacturing	
Span	3	4	0	0	0	0	1	1	1	0	0	1	1	1	1	
AR	3	4	0	0	0	0	1	1	1	0	0	1	1	1	1	
Λ	5	9	0	0	0	0	1	1	0	4	1	4	4	4	4	
λ	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
t/c	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
camber	4	0	0	0	9	0	1	1	4	0	4	1	4	4	4	
		69	0	0	36	0	15	15	22	20	21	30	-42	-42	-42	102
																Morphing Capability Score

Figure II-5. QFD Table for Determining the MCS for the Third Iteration of the MCL Tool

to develop a tool that would couple the MIS and the MCS into one number that would describe the morphing vehicle. The product of the two values was the natural extension of this desire. Figure II-6 shows an example calculation that was performed to vet the process.

MCL = MIS * MCS

F-111
MCL = 1.0 $\times$ 70
MCL = 70

F-111MAW
MCL = 1.5 $\times$ 1.02
MCL = 117

Figure II-6. Determination of the Final MCL Score

While this approach was more quantitative, it still did not fully satisfy the need for an assessment that described morphing vehicles, the technologies required to enable the morphing, and impact of these technologies on a given mission. The primary issue was the final output value of the MCL analysis. While a single number to describe the level of morphing was desirable, no frame of reference existed for the MCL number. The only way that any frame of reference could be attached to the MCL number was by doing the analysis for conventional vehicles and inferring what the MCL number meant. This would have been possible for morphing vehicles that were evolutionary developments from traditional vehicles. However, since the goal of morphing was to enable revolutionary missions, any framework that required the use of a conventional vehicle as a baseline would limit the usefulness of the tool. With this realization, the current MCA process was developed and allowed the user to evaluate a morphing vehicle independent of any traditional vehicle or fixed frame of reference.

B. THE CURRENT MCA PROCESS

The current MCA tool is a result of and combination of the processes discussed in the previous section. The first portion is the Morphing Concept Assessment (MCoA) process. The MCoA uses quantitative analysis and QFD to arrive at a morphing capability sketch that captures the mission performance improvement, technology application, and risk associated with a morphing vehicle. The second portion is the Morphing Capability Development Level (MCDL). While the MCoA provides a quantitative assessment of the vehicles in question, it does not indicate progress toward an ideal morphing vehicle. The MCDL is designed to allow tracking the progress toward this ideal vehicle t and aids in identifying areas where progress has been lacking.

The MCoA process begins with the premise that a given mission has been conceived and ends with an assessment of different potential morphing solutions and related technologies required to accomplish it. The MCoA's goal was to develop a way to relate mission-driven aircraft design parameters with the proposed technologies to meet those mission goals. The intention was not to revert back to a mission-based requirements definition; rather, it was an attempt to assess the impact that certain technologies have on aircraft performance. Figure II-7 shows the three very distinct but intimately related steps in the MCoA process:

- **Step 1: Determine the MIS.** The vehicle's relationship to mission scenarios and required performance is established. The output of Step 1 is the MIS, a number that reflects the relative performance of the proposed vehicle to its desired performance.
- **Step 2: Evaluate the MCS.** This step is divided into two parts, both of which use a modified QFD scheme to assess the impact of technology on morphing. The first part considers technology impacts on vehicle performance, while the second part assesses schedule and technology risk for the selected technologies. These two items were separated to allow project managers and technology futurists to gauge better the risk/reward relationship

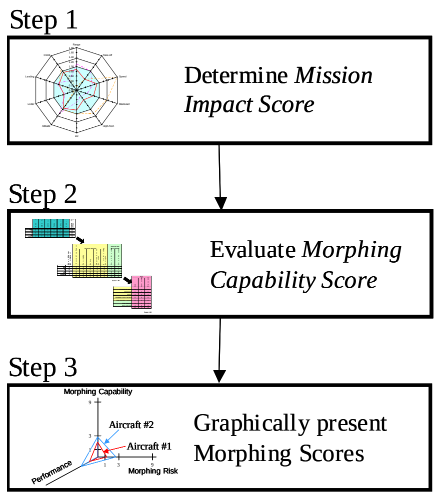


Figure II-7. Outline of the Current MCoA Process

for different technologies. The QFD approach was selected because it allows a multidisciplinary assessment of technologies to determine how they impact vehicle performance (Ref. 4).[3]

- **Step 3: Graphically present morphing scores.** The final step of the MCoA is to plot the results on a 3-D graph that has performance on one axis, technology effects on the second, and technology risk on the third. Plotting all three pieces of information on one graph allows the comparison of risk with reward for multiple concepts.

As with any codified process, misleading answers can be a result. As the MCoA was developed, a significant amount of attention was paid to the problem of providing leading answers to drive the assessment toward a high score. In Step 1 of the MCoA, one area of concern was unintentionally rewarding a secondary aspect of the design that far exceeded the requirement at the expense of a critical morphing design aspect. It was feared that this attribute of the MCA tool could be used to skew the resulting score. Accounting for this aspect of the MCoA design has an additional benefit: noncritical morphing features are not unduly penalized for not meeting requirements. This effect was limited by using a weighted average to determine the MIS. In general, based on the proposed mission, the program management team will provide the weights that are attached to performance parameter in the MIS.

3 Unfortunately, a means does not currently exist to do the reverse (i.e., know what vehicle performance changes are required and develop a technology list that would enable them). This is a limiting factor not only for the MCL process, but also for all technology development assessment tools.

As mentioned earlier, for Step 2, a modified QFD process was used. This process is inherently robust because of the scoring method. Since the scoring is based on the 0, 1, 3, or 9 scale, where the scores reflect zero, small, moderate, or large contributions to the state change of the vehicle, the process leads to large steps so that the user will not become bogged down in slight differences between levels.

The MCoA process will be outlined in the following discussion. The process will only be discussed in general terms in this section while a worked example is provided later in the report.

1. The MCoA Process

a. Step 1: Weighted Average Methodology

In the first step, the relationship between mission scenarios and required vehicle performance metrics is established. Generally, mission scenarios developed by the users will identify key vehicle performance characteristics required to accomplish those scenarios. The connection between the vehicle performance parameters and mission-defined key vehicle performance characteristics is represented on a performance-space "spider plot" (see Figure II-2). This plot allows comparison among performance characteristics of current, newly proposed, and/or envisioned vehicles. It also provides a clear illustration of advancements needed in vehicle performance to fulfill the desired mission. It should be expected that the mission-defined vehicle performance characteristics would contain contradictory design requirements (e.g., combining long endurance and high dash speed requirements for an aircraft so that feasible solutions can only be achieved by significant vehicle state changes).

Using the given vehicle performance requirements, a weight is assigned to each capability parameter according to its importance, with a sum of the weights equaling 1. For example, for some proposed missions that morphing will likely enable, one capability might be judged as being more important than another capability. This would result in its weight being judged higher than other capabilities. Using the information from the performance space, a compound number that represents the MIS for the given vehicle [see Figure II-8)] can be determined. The MIS can be determined from different combinations of normalized performance parameters [e.g., simple mean, geometric mean, root-mean-square (rms), weighted mean, and so forth]. Advantages and shortcomings of some of these means are discussed in Section III.

	Desired	Aircraft #1	Aircraft # 2	Aircraft # 1 Ratio	Aircraft # 2 Ratio	Weights
Range	4000	3600	4400	0.90	1.10	0.175
Take-off	3500	3110	3900	1.13	0.90	0.025
Max Speed	950	950	950	1.00	1.00	0.100
Maneuver	6.00	6.00	6.00	1.00	1.00	0.125
Endurance	5.00	5.00	5.00	1.00	1.00	0.150
Cruise Speed	0.75	0.75	0.75	1.00	1.00	0.100
Altitude	65000	65000	65000	1.00	1.00	0.100
Loiter	4.00	4.00	4.00	1.00	1.00	0.150
Landing	4500	4000	5000	1.13	0.90	0.025
Climb	5000	5000	5000	1.00	1.00	0.050

	Weighted	Median	Sum	Avergae
Aircraft # 1	**0.99**	**1.00**	**10.15**	**1.02**
Aircraft #2	**1.01**	**1.00**	**9.90**	**0.99**

Figure II-8. Example of a Mission Impact Table

Using the given mission capability desired, the ratio of the vehicle's ability to meet that capability is assessed. Multiplying by the weight and adding all mission segments together results in the Mission Performance Index (MPI). Figure II-8 shows a sample table with varying capability weights and the resulting MPI.

b. Step 2/Part A: Mission Impact

The overall goal of Step 2 is to define and assess the impact of morphing technologies on the vehicle's performance. The approach requires that the performance parameters be related to vehicle state changes, the means to achieve such changes, and the enabling technologies available/to be developed and their corresponding technology development risks (including costs). This results in three sub-steps that make up the core of the second step in the MCoA process. The overall process for Step 2 was developed based on a modified QFD approach.

Figure II-9 illustrates the three substeps. First, the sensitivity of different state change parameters is mapped against key performance metrics determined from the MCoA Step 1. For this, already existing and new design tools that can perform the tradeoffs between morphing features are required. In the aircraft example, this reflects how wing area, aspect ratio, camber, and so forth can affect vehicle performance parameters such as loiter time, range, dash speed, and so forth. At the end of this substep, the most effective state change parameters are ranked. Using these, morphing methods/schemes that can achieve those state changes are measured for effectiveness in performing the desired changes. These state changes can then be related to/linked to appropriate technologies necessary to achieve the required state changes.

Part 1 – State Change Effectiveness

Physical State Change		Max. Speed	Climb Rate	Landing Dist.	Take-off Dist.	Manueverability	Others	State Change Effectivness
	Span	5	3	4	4	3	...	4
	AR	3	2	3	3	2	...	3
	Λ	5	3	5	5	4	...	4
	λ	1	1	1	1	1	...	1
	t/c	1	1	1	1	1	...	1
	camber	2	2	5	5	5	...	4

Part 2 –Capability Score

		Morphing Methods					Materials and Technologies	
	State Change Effectivness	Pinned Wing Sweep	Telescoping	Folding	Hingeless Control Surfaces	Other Morphing Concepts	Smart Materials	Smart Actuators
Span	3	3	0	0	0	0	1	1
AR	3	3	0	0	0	0	1	1
Λ	5	9	0	0	0	0	1	1
λ	1	0	0	0	0	0	0	0
t/c	1	0	0	0	0	0	0	0
camber	4	0	0	0	9	0	1	1
		63	0	0	36	0	15	15

Score = *XX*

Part 3 – Risk Assessment

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	1	1	1
Telescoping	1	1	1
Folding	3	3	3
Hingeless Control Surfaces	0	0	0
Other Morphing Concepts	0	0	0
Smart Materials	3	3	3
Smart Actuators	3	3	3
	11	11	11

Score = *XX*

Figure II-9. Three Parts of Step 2 of the MCoA Process

c. Step 2/Part B: QFD Analysis of Morphing Methods and Technologies

Step 2 begins the evaluation of the technologies that would enable the morphing capabilities of the concepts. Using the QFD methodology, an assessment is made of the amount of morphing an aircraft undergoes and the technologies enabling the changes. The QFD process was developed originally to help multidisciplinary organizations focus on customer requirements. The qualities important in identifying customer needs, namely nonevenly distributed scoring to differentiate between "low-medium-high" impact, technology identification, and relative importance recognition, are the same as those necessary to quantify morphing capability.

d. Step 2/Part C: QFD Analysis of Risk

Not only are the technologies that enable morphing important, but the risks that these advanced technologies entail are also critical. Since technical and programmatic risk is an important factor in the selection and management of projects, it was decided that the MCA tool should incorporate a section that allows technical and programmatic risks to be tracked. Starting with the morphing methods and technologies identified in Step 2/Part B, a low-medium-high risk assessment was assigned and a QFD-based assessment was made. The goal was to allow the user of the MCoA and the MCA to evaluate separately the technologies and the associated schedule and financial risks that accompany morphing.

e. Step 3: Plot Values From Step 1 and Step 2 on a 3-axis Graph

The third and final step of the MCoA process presents the relative morphing capability of the compared vehicles and the technologies on a graph. For MCoA Step 3, the three morphing scores (the Morphing Performance Impact, the Morphing Capability, and the Morphing Risk) are plotted on a 3-axis graph as shown in Figure II-10.

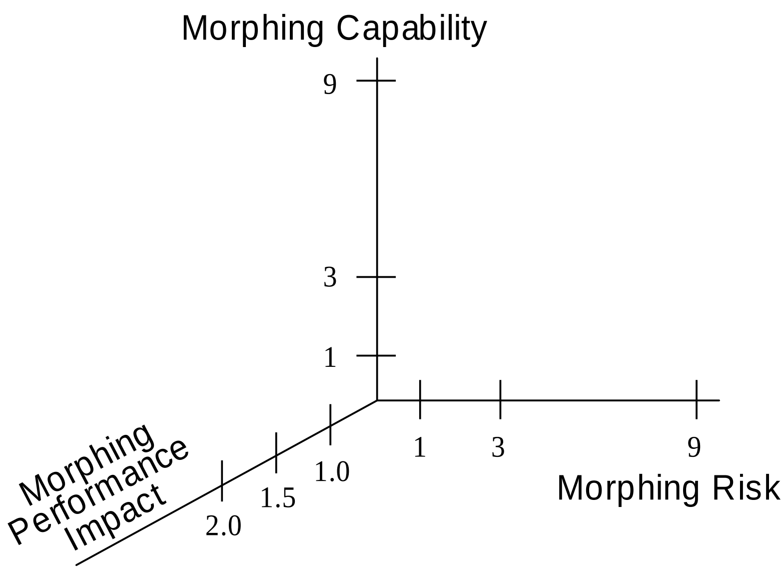


Figure II-10. A 3-Axis Plot for Step 3 of the MCoA Process

2. Development of the MCDL Table

While the MCoA process allows the comparison and assessment of potential morphing systems, it does not aid in determining the progress toward the ideal morphing vehicle or identifying areas that need attention. To assist in this, the final step in the MCA is the development of the MCDL table. This table contains vehicle-specific and vehicle-independent features broken down into 10 levels, which qualitatively describe the progress toward ideal morphing. Figure II-11 shows a typical table for aircraft.

	Vehicle-independent Features				Vehicle-specific Features		
Level	**Mission Effectiveness**	**State Change/Efficiency**	**Adaptability to Environment and/or Threat**	**Generalized Cost ($, weight, complexity, power, reliability)**	**Lift Generation Surfaces**	**Maneuvering Capability**	**Survivability/Maintainability**
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat- cannot be done with other methods	Great improvement over existing methods - from component to system levels	Conformally deployed lifting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability/maintainability on demand
9	Enable new mission with improved effectiveness	Large state change - competes with existing methods	Great adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level			Self-healing systems
8	Enable new mission	Large state change - inefficiently replaces existing methods	Great adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the weapon system level		Conformally deployed control surfaces from wing-fuselage	
7	Combining (dissimilar) existing missions with superior effectiveness	Moderate state change - exceeds performance of existing methods	Moderate adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon system level			
6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
5	Combining (dissimilar) existing missions inefficiently	Moderate state change - inefficiently replaces existing methods	Moderate adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the vehicle level	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Aircraf re-trimming after failure/damage, store/load changes, etc.
4	Perform existing missions with superior effectiveness	Minimal state change - exceeds performance of existing methods	Minimal adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the vehicle level	Conformal lifting surfaces sweep and/or surface area change	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw	Vehicle real-time reconfigurable flight envelop based on usage and health monitoring information
3	Perform existing missions with improved effectiveness	Minimal state change - competes with existing methods	Provides minimal adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the component level	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes for secondary flight controls; increase maneuverability and decrease vulnerability	In-flight active loads re-distribution
2	Perform existing missions with current effectiveness	Minimal state change - inefficiently replaces existing methods	Provides minimal adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the component level	Discrete lifting surface sweep and/or area change	Conformal lifting surface changes driven by discrete surfaces	Vehicle usage and health monitoring
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features	No special features

Figure II-11. MCDL Table for Morphing Aircraft Systems

The table in Figure II-11 is broken down into two sections. The first section lists vehicle-independent features. These are elements of the vehicle that are not dependent on the medium (i.e., air, water, land, or space) in which it operates. Currently, four features are assessed: mission effectiveness, state change efficiency, adaptability to environment and/or threat, and generalized cost. The other section identifies vehicle-specific features affected by morphing. These include, for example, wing shape for aircraft, and hull shape and draft for ships. In general, the development of vehicle-specific features is more difficult than is the development of vehicle-independent features. By comparing and updating the specified levels in the MCDL, progress toward an ideal morphing vehicle can be tracked, and areas where further development is required can be identified.

III. EXAMPLE APPLICATION OF AN MCA

To illustrate the proposed assessment process, consider that an advanced aircraft designed to perform a strike/attack mission is sought (a type of mission that might have been desirable in the 1970s). The objective is to accomplish an existing mission (i.e., strike/attack) with improved effectiveness (e.g., deeper strike range, extended time-on-station, and increased vehicle maneuverability).

A set of performance metrics that a potential new aircraft must fulfill is derived from the mission requirements. Table III-1 summarizes the mission performance metrics for this example.

Table III-1. Notional Metrics Used for Potential New Aircraft

Mission Performance Parameters	Desired Value
Range (nm)	4,000
Takeoff Distance (ft)	3,500
Maximum Speed (kt)	950
Maneuver Limit (g's)	6
Endurance (hr)	5
Cruise Mach No.	0.75
Maximum Altitude (ft)	65,000
Loiter Time (hr)	4
Landing Distance (ft)	4,500
Climb Rate (ft/sec)	5,000

A. STANDARD F-111 vs. ADVANCED FIGHTER TECHNOLOGY INTEGRATION (AFTI) F-111

Consider two notional aircraft as contenders to enable this new mission. Aircraft #1 is a supersonic, fighter/attack aircraft that has features similar to the General Dynamics F-111. Aircraft #2 is another fighter/attack aircraft. It is similar to Aircraft #1 but has a particular morphing feature. This second aircraft is based on the F-111 Mission Adaptive Wing (MAW) airplane from the AFTI programs (Ref. 5).Both aircraft have variable sweep wings. Aircraft #2 has adaptive leading- and trailing-edge control surfaces that allow smooth variable camber wings and contain the control system required to adjust the wing in response to different flight conditions. The conventional control surfaces on each wing are replaced by gapless surfaces that allowed the wing shape to be optimized for landing, cruise, and high-speed dash. As an example, Figure III-1 shows how the AFTI F-111 wing shape changed for different lift vs. drag requirements. While not an example of a vehicle that has comprehensive morphing capabilities, it provides an initial test case to demonstrate the use of the MCA process.

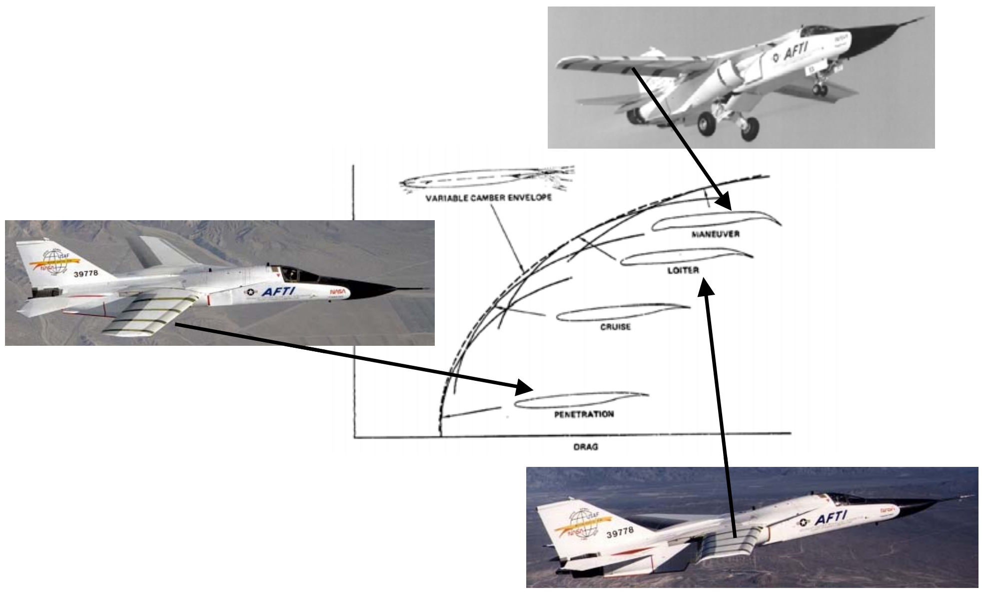


Figure III-1. F-111/AFTI Aircraft Used as Basis for the MCA Example

The selected performance parameters identified are notional and are selected to include typically two disparate mission requirements that have competing design requirements—in this case, long loiter time and high-speed dash. For the aircraft invented for the example, the maximum range, aircraft maneuverability, endurance, and loiter were selected as the most important performance parameters.

B. MCA PROCESS FOR A STANDARD F-111 VS. AFTI F-111

1. The MCoA Process

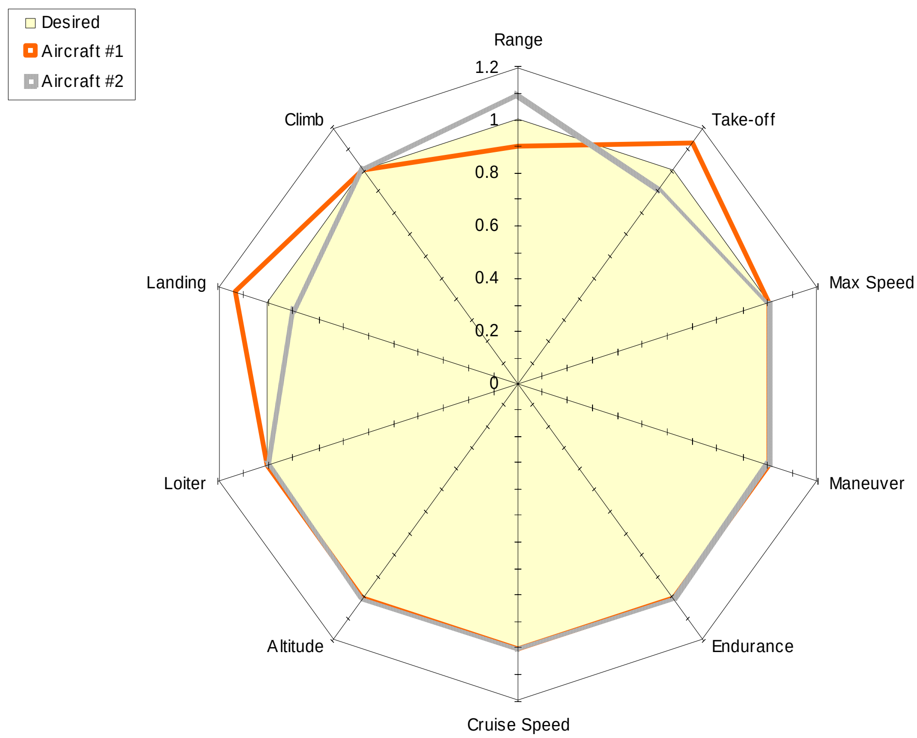
a. Step 1: Apply Weighted Average Methodology and Spider Plot

To arrive at the MPI score (the vehicle score that describes how the aircraft performs the given mission), a weighted average can be used for the individual aircraft performance ratios. For the example chosen, both a simple average and a weighted average calculation were done to show why the weighted average is currently the preferred method to calculate MPI. If a simple average is used, the MPI for Aircraft #2 is 1.04 while that for Aircraft #1 is 1.00. What these numbers imply is that Aircraft #2 would generally outperform the desired mission performance goals by 4 percent while Aircraft #1 meets the desired mission performance criteria. While a well-selected set of performance metrics characterizes the desired mission, not all metrics have the same mission impact. In fact, the MPI score can be skewed because one potentially unimportant performance metric is greatly different from what is required. To address this issue, a weighted average function is used to ensure that the most critical mission performance metrics count the most toward the MPI score. To determine the weights, the evaluator assigns a weight to each metric by setting the higher weights for the attributes that are significant and reducing the weight for the less important ones.

A numerical example of how the standard average calculation can misinterpret the relative performance effectiveness of each aircraft is shown in the two left columns in the table of Figure III-2. For this strike/attack mission, it is assumed that range of the aircraft is a much more important metric than takeoff and/or landing distances (within reason). This is reflected in the choice of weights: 0.175 for range and 0.020 for takeoff/landing distance. The rankings show that if a simple average was used to calculate MPI, Aircraft #1 and #2 would be rated very closely. However, this is not a true reflection of each aircraft's ability to meet the defined mission scenario. On the other hand, using the weighted average gives Aircraft #2 the higher MPI value: 1.05 vs. 0.93 for Aircraft #1. The higher MPI indicates that Aircraft #2 better satisfies the performance metrics that represent the desired mission. It clearly scores higher in the categories that were deemed more important (range, loiter, endurance, and maneuver capability for this particular example), and, therefore, those categories were assigned higher weights.

b. Step 2/Part A: Identify Morphing Technologies and Determine Mission Impact of Identified Morphing Technologies and Performance Parameters Affected

For this example, a three-part QFD analysis is applied. The first part involves determining the effectiveness of selected state changes on individual performance metrics. This was established in Step 1, and is, therefore, linked directly to the mission effectiveness. Values from 1 (lowest) to 5 (highest) are used to quantify the impact. For the current example, physical characteristics that could be changed by morphing the wing



	Desired	Aircraft # 1 Ratio	Aircraft # 2 Ratio	Weights
Range	4000	0.95	0.98	0.175
Take-off	3500	1.30	1.00	0.020
Max Speed	950	0.85	0.98	0.100
Maneuver	6.00	0.85	1.10	0.125
Endurance	5.00	0.95	1.10	0.150
Cruise Speed	0.75	1.00	1.07	0.100
Altitude	65000	1.00	1.00	0.100
Loiter	4.00	0.85	1.15	0.175
Landing	4500	1.30	1.00	0.020
Climb	5000	0.90	1.00	0.035

	Median	Sum	Average	Weighted
Aircraft # 1	0.95	9.95	1.00	0.93
Aircraft # 2	1.00	10.37	1.04	1.05

Figure III-2. Mission Impact RADAR Plot and Weighted Average Score for Example Aircraft

are the wing span, wing aspect ratio (AR), sweep angle (Λ), taper ratio (λ), wing thickness-to-chord ratio (t/c), and wing camber. The scores for each physical state are determined through a combination of numerical simulations, knowledge of the morphing vehicle being evaluated, and an understanding of how the physical changes affect each of the selected performance metrics. Figure III-3 summarizes this. The simple average of the scores (rounded to the nearest integer) for each state-change effectiveness rating (right column in Figure III-3) will be used as the weight in the calculation of the MCS. For Aircraft #1 and #2, the span change, sweep angle (Λ), and camber change were rated high and given average scores of 4.

Physical State Change		Max. Speed	Range	Landing Dist.	Take-off Dist.	Manueverability	Others …	State Change Effectivness
	Span	5	4	4	4	3	…	4
	AR	3	4	3	3	2	…	3
	Λ	5	3	5	5	4	…	4
	λ	1	2	1	1	1	…	1
	t/c	1	2	1	1	1	…	1
	camber	2	2	5	5	5	…	4

Figure III-3. MCoA Step 2/Part A:
Mission Impact Assessment of Selected Physical State Changes

Taper ratio (λ) and thickness-to-chord ratio (t/c) were not as important to the given mission and were rated only as 1, the lowest value. The average of these values is then placed in the left-most column of the QFD matrix for Part B (see Figure III-4).

Aircraft #1

Physical State Change		State Change Effectivness	Morphing Methods: Pinned Wing Sweep	Telescoping	Folding	Hingeless Control Surfaces	Other Morphing Concepts	Materials and Technologies: Smart Materials	Smart Actuators	Other Technologies
	Span	4	3	0	0	0	0	1	1	...
	AR	3	3	0	0	0	0	1	1	...
	Λ	4	9	0	0	0	0	1	1	...
	λ	1	0	0	0	0	0	0	0	...
	t/c	1	0	0	0	0	0	0	0	...
	camber	4	0	0	0	0	0	1	1	...
			57	0	0	0	0	12	12	...

Overall Score **81**
Capability Score **0.8**

Aircraft #2

Physical State Change		State Change Effectivness	Morphing Methods: Pinned Wing Sweep	Telescoping	Conventional, Hinged Trailing Edge Control Surfaces	Hingeless Control Surfaces	Other Morphing Concepts	Materials and Technologies: Smart Materials	Smart Actuators	Other Technologies
	Span	4	3	0	0	0	0	1	1	...
	AR	3	3	0	0	0	0	1	1	...
	Λ	4	9	0	0	0	0	1	1	...
	λ	1	0	0	0	0	0	0	0	...
	t/c	1	0	0	0	0	0	0	0	...
	camber	4	0	0	0	9	0	1	1	...
			57	0	0	36	0	15	15	...

Overall Score **123**
Capability Score **1.1**

Figure III-4. MCoA Step 2/Part B:
Connecting Morphing Methods and Technologies to State Changes

c. Step 2/Part B – Complete Performance Quality Function Deployment (QFD)

The next step links morphing methods and technologies to the physical state changes. Figure III-4 illustrates this for both example aircraft. The means and methods used to achieve morphing are placed in vertical columns and scored with a 0, 1, 3, or 9 depending on whether they make zero, small, moderate, or large contributions to the physical state change of the vehicle. Returning to the example, Aircraft #1 and Aircraft #2 share a common characteristic, namely, a variable sweep wing. Aircraft #2, however, has variable camber leading and trailing-edge control surfaces that could be used to tailor the wing shape more precisely for landing, takeoff, cruise, and dash. This difference is reflected in the "Hingeless Control Surface" column, where the value is 0 for Aircraft #1 and 9 for the Aircraft #2. The capability score given to each aircraft is a normalized average, with the normalizing value being 9 times the number of nonzero boxes in the QFD matrix (i.e., the maximum score possible). As the scores show, Aircraft #2 receives a higher MCS. This was expected because of the inclusion of the highly adaptive leading- and trailing-edge control surfaces. As morphing capabilities and use of smart structures increase, the MCS scores will rise above the "low" value seen in this example.

4. Step 2/Part C: Identify Risk Areas and Perform Risk Quality Function Deployment (QFD)

While knowing that an aircraft has a higher morphing capability is important, assessing the risk in development and operations would also provide much needed information to the PM who selects which concept to fund or to the system developers seeking to identify risk early in a program.

This is the core of Step 2/Part C of the MCoA process. The risk assessment is done using a similar QFD approach to that used in Step 2/Part B. For the risk assessment, the items of interest (i.e., mechanisms and technologies) are placed in the left column as shown in Figure III-5. They are compared with areas of risk including, but not limited to, cost, schedule, and manufacturing. The columns are then multiplied together and summed, and the normalized average is determined (as in Part B) to arrive at the risk score. As would be expected for the aircraft selected in our example, Aircraft #2 showed a much higher risk score than Aircraft #1 because of the variable leading and trailing edges. The higher risk does not necessarily mean that the project is not warranted.

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Folding	0	0	0
Hingeless Control Surfaces	0	0	0
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Smart Actuators	1	1	1
	5	5	3
	Risk Score		**1.08**

Aircraft #1

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Folding	0	0	0
Hingeless Control Surfaces	3	9	3
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Smart Actuators	1	1	1
	8	14	6
	Risk Score		**2.33**

Aircraft #2

Figure III-5. MCoA Step 2/Part C: Risk Assessment

It indicates only that certain aspects of the cost, complexity, schedule, and/or manufacturing require attention and vigilance to reach successful completion. The risk analysis portion of the MCoA framework is meant to identify technology areas that require extra attention.

e. Step 3: Plot Results From Step 1 and Step 2 on a 3-axis Graph

Step 3 in the MCoA process is simply plotting the relative scores from Steps 2A, 2B, and 2C onto a 3-axis plot (see Figure III-6). One axis is the MPI (Mission Performance Index), the second axis is the MCS (Morphing Capability Score), and the third axis is a measure of the risk assessment. This plot allows a graphical comparison of each vehicle in terms of its performance, morphing capability, and risk for a desired mission. Initially, the MCoA tool's goal was to arrive at a single number that could be used to rank morphing concepts. With the continuing development of this assessment process, what has become clear is that one number provides little information for assessing performance benefits, morphing ability, or risk associated with morphing concepts. In lieu of this single number, the graphical representation shows how the vehicles compare in the three critical areas.

To help make the comparison between vehicles easier, the plots can be unfolded and the projection of each side of the triangle can be plotted. Figure III-6 shows the projection plots. The projection plots can be especially useful during technology

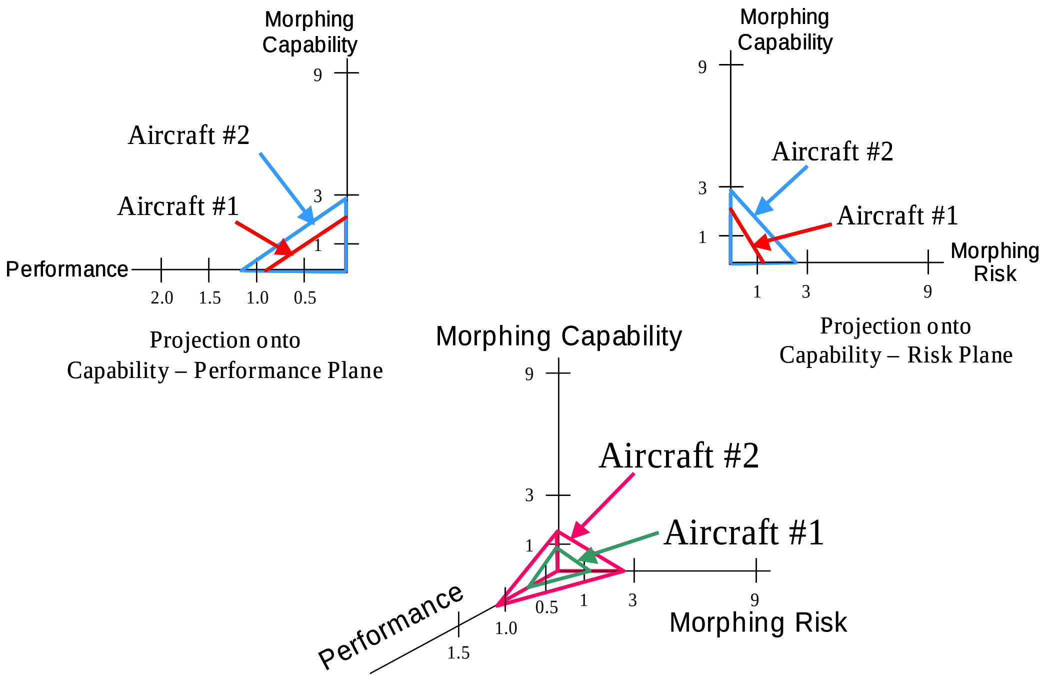


Figure III-6. MCoA Step 3: Comparison of Different Morphing Concepts

development phases for which adequate information may not be readily available to complete the entire assessment. As can be seen from Figure III-6, Aircraft #2 scores higher in all the categories including risk.

2. Development of the MCDL Table

While the MCoA tool provides the ability to assess proposed vehicle and technology concepts relative to achieving desired mission capabilities, the MCDL table is intended to provide a broader, more qualitative view of morphing capabilities *and* goals for future vehicle systems. It must present the progression of key attributes from the current aircraft to a final set of desired features based on the morphing vehicle system objectives. These objectives must be set *a priori* as a reflection of a long-term vision on morphing development. Thus, the MCDL table could serve as a program-planning tool to indicate general directions and goals for technology and vehicle system morphing capability advancement.

The vehicle system attributes to be considered in the MCDL table are grouped in sets of vehicle-independent and vehicle-specific features. Figure III-7 presents an initial representation of such a table and its feature development phases. In this particular case,

Level	Vehicle-independent Features				Vehicle-specific Features		
	Mission Effectiveness	State Change/Efficiency	Adaptability to Environment and/or Threat	Generalized Cost ($, weight, complexity, power, reliability)	Lift Generation Surfaces	Maneuvering Capability	Survivability/Maintainability
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat-cannot be done with other methods	Great improvement over existing methods - from component to system levels	Conformally deployed lifting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability/maintainability on demand
9	Enable new mission with improved effectiveness	Large state change - competes with existing methods	Great adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level			Self-healing systems
8	Enable new mission	Large state change - inefficiently replaces existing methods	Great adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the weapon system level		Conformally deployed control surfaces from wing-fuselage	
7	Combining (dissimilar) existing missions with superior effectiveness	Moderate state change - exceeds performance of existing methods	Moderate adaptability to environment and/or threat-cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon system level			
6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
5	Combining (dissimilar) existing missions inefficiently	Moderate state change - inefficiently replaces existing methods	Moderate adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the vehicle level	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Aircraf re-trimming after failure/damage, store/load changes, etc.
4	Perform existing missions with superior effectiveness	Minimal state change - exceeds performance of existing methods	Minimal adaptability to environment and/or threat-cannot be done with other methods	Inneficient w.r.t. existing methods - at the vehicle level	Conformal lifting surfaces sweep and/or surface area change	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw	Vehicle real-time reconfigurable flight envelop based on usage and health monitoring information
3	Perform existing missions with improved effectiveness	Minimal state change - competes with existing methods	Provides minimal adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the component level	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes for secondary flight controls; increase maneuverability and decrease vulnerability	In-flight active loads re-distribution
2	Perform existing missions with current effectiveness	Minimal state change - inefficiently replaces existing methods	Provides minimal adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the component level	Discrete lifting surface sweep and/or area change	Conformal lifting surface changes driven by discrete surfaces	Vehicle usage and health monitoring
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat-inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features	No special features

Figure III-7. MCDL Table With Morphing Aircraft Results

the vehicle-specific features are considered for an air vehicle. Ranging from no special feature to a full morphing realization, each feature stream (column) is subdivided into 10 levels.

The vehicle-independent features describe desired characteristics of a vehicle independent of its operational environment (i.e., air, water, land, space, or some combination of these environments). The "Mission Effectiveness" column captures the desire to perform existing missions and combinations of existing missions and to enable new missions. It is also desired that the vehicle present great adaptability to the environment and to threats. Since the focus to achieve these features is through state changes, the morphing development should progress in such a way that will eventually lead to large state changes. Finally, overall cost assessment of the methods employed in the morphing realization, from component to the system level, must be such that it provides great improvements over existing methods.

The vehicle-specific part of the MCDL table is much more complex to establish. It involves identifying key features that characterize the vehicle class (i.e., operational media) under consideration. Once such characteristics are defined, envisioned phases of development, which range from those requiring no special features to those requiring special features for a complete morphing vehicle, must be developed for each of those key features. As a first attempt to identify some of these key features and their envisioned developmental stages toward a complete morphing air vehicle, three specific features are proposed: lift generation surfaces, means of maneuvering (represented in the table under the "Maneuvering Capability" column), and survivability/maintainability, particularly during flight operations. Inspired by the form and function of biological systems, the desired morphing aircraft would conformably deploy lifting surfaces, provide high-bandwidth maneuver forces and moments, and present adaptability/maintainability on demand. These vehicle-specific streams are important to help guide the research investment for the development of specific features associated with a vehicle being operated in given media. In contrast, the vehicle-independent features ultimately need to be present in a new system that will satisfy the stated needs.

To aid in general program planning, morphing concepts must be assessed in terms of a high-level vision of the desired features of the weapon system. Consider the MCDL table presented in Figure III-7 as an initial representation of that high-level vision. In the context of the preceding example, Aircraft #2 presents certain key vehicle features that can be mapped onto the MCDL table. The dashed dots and lines in Figure III-7 show these features. The advanced strike/attack mission can be seen as a Level 3 under "Mission Effectiveness." Similarly, the camber changes are reflected as small state changes in the context of morphing state changes. Although the extra maneuverability provided by the small reshaping of the wing increases its survivability, the vehicle only provides minimum adaptability to the environment and/or threats, as reflected in the Level 2 score in the corresponding column in the MCDL table. Considering that the physical realization of the camber change mechanisms for Aircraft #2 follows the one used in the AFTI F-111, the additional mechanical complexity and potential weight penalty will have a negative impact on costs. This would be indicated in Figure III-7 as a Level 1 score. In terms of vehicle-specific features, Aircraft #2 does provide an advance on the lift generation surface features, thereby achieving Level 3 because of the presence of the airfoil shape change associated with camber deformation. This also provides an increase in maneuverability and changes in secondary flight controls through the adjustment of the wing shape in different mission segments. Finally, Aircraft #2 does not present any special feature for improved maintainability or survivability.

With these results, if the Aircraft #2 concept goes forward and is developed, progress will be made in certain features that support the morphing objectives [as indicated in the MCDL table (see Figure III-7)]. On the other hand, such a program will not address certain key features that will be part of a complete morphing aircraft, and new development programs in those areas will be necessary to attain the complete morphing objectives. By representing different programs using this common framework and process, PMs and researchers will be able to see which features are being developed and which ones are lagging and need more attention. In the preceding example, as a next step toward further development on survivability/maintainability, such an approach may drive the funding allocation for new programs in the direction of issues associated with integrated vehicle health management systems (since this is still at Level 1 in Figure III-7).

IV. AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS (AIAA) STRUCTURES, STRUCTURAL DYNAMICS, AND MATERIALS (SDM) PANEL SESSION

A panel discussion session of the paper *A Framework for Morphing Capability Assessment* (Ref. 6 and Appendix A) was held at the 12th AIAA/ASME/AHS Adaptive Structures Conference, in conjunction with the 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (Palm Springs, California, in April 2004).

The goal of the panel discussion was to

- Present the current status of a developing morphing capability assessment tool
- Solicit feedback from potential users and other interested parties to shape further development of the MCA process.

The panel discussion session consisted of the authors' presentation of their paper followed by briefings from industry panel members. The panel consisted of the following members:

- Charles Chase, Lockheed Martin
- Shiv Joshi, NextGen Aeronautics
- Don Uhlir, Raytheon
- Ed White, Boeing
- Carlos Cesnik, University of Michigan
- Howard Last, Institute for Defense Analyses (IDA)
- Chris Martin, Institute for Defense Analyses (IDA).

Appendix B contains the briefing presented at the panel discussion.

Industry panel members were asked to address issues that would facilitate discussion during the panel session. In particular, the members were asked to address as many of the following points as possible:

- Explain how your organization performs similar processes now. An outline of existing practices may provide ways to improve the MCA process or may facilitate its introduction into a program technology selection process.
- Present the results of an example of using the current MCA process, if you and your development team worked an example.[4]
- Discuss the following using your example or the example presented in the paper:
  - Utility of this tool as part of a program technology selection process, including
    - Issues and concerns associated with the process and, if continued development is warranted
    - Your organization's potential role in future development.
  - Ease of use, including
    - Overall process
    - Individual parts/steps
    - Length of time to work through an example, identifying the features and steps that most affected time.
  - Assumptions made to complete the process and the impact of these assumptions on any technology observations/conclusions that are drawn, including
    - General assumptions that apply throughout the process
    - Assumptions needed for particular step.
- Present specific suggestions to improve the tool/process.

The authors of this report and Dr. William Hong of IDA, who acted as moderator for the panel, took notes and prepared general observations from the panel discussion. These general observations are documented in this report and address issues raised, especially those observations dealing with any confusion raised by the presented paper.

Most panel members recognized the difficulty of what the MCA process is attempting to accomplish. The difficulty arises because the total potential benefit from using morphing technologies will be realized at the system level and not at the

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4 The panel members did not work an example using the proposed MCA tool. Some panel members presented information related to their company's processes used for current morphing aircraft R&D programs.

component level. In addition, complete system architectures using a "system-of-systems" approach can consist of multiple vehicle systems. From the outset, the MCA process was developed for a single-vehicle system and was not intended to assess more than one vehicle system at a time (although its basic principles can be carried over to multiple vehicles as part of a large system).

An additional difficulty is that many assumptions have to be made throughout the process. The assumptions must be clearly stated so as to have traceability to the results of the process and to allow for comparisons of results from different analyses using the process. The authors note that the fact that assumptions have to be made is consistent with other technology assessment processes and tools currently in use (e.g., the TRL process). Another concern was the different levels of fidelity in the analyses from various organizations using this process. The authors acknowledge that this is true of this process and of other assessment processes in use. The value to developers and PMs may lie in the identification and resolution of differences in the analyses performed using this process.

Most of the panel members presented thoughts on system performance metrics that should be used when attempting to understand benefit of morphing based on "mission impact." First, it was stated that the mission performance impact was a multi-dimensional space that added to the difficulty of representing the potential benefits of using morphing technologies in a system. It was suggested that a minimum set of mission performance axes or metrics should be chosen to aid in keeping the process simple and manageable. Second, the performance metrics should be clearly linked to mission cost effectiveness. What does the performance enhancement buy the customer in terms of mission cost (e.g., a reduced number of aircraft needed, reduced number of sorties flown, reduced "cost per kill") for a given system concept? Finally, most attendees could see how the process might apply to a given vehicle system, but expressed concern about how the process might apply to a multivehicle system.

In summary, the following general observations were made:

- Most panel members determined that the process was too complex to be useful. This assessment was based mainly on the 1-hour briefing given by the authors. Despite making the conference paper (Ref. 6) available to the industry panel members well in advance of the session, it did not appear that it had been studied in depth. As a result, significant time was spent during the panel session explaining the MCA role and process.
- Considerable concern was expressed about how the results from this process might be used by government PMs. The use of a structured, independent tool

such as the MCA concerned panelists and generated a feeling of a potential "government regulation." The industry members were concerned that the use of data generated from analysis tools used during preliminary design would not contain sufficient fidelity to make a reasoned determination of performance using spider plots. The panelists thought that the current method of using low-fidelity analysis tools, trial-and-error, and expertise from developers provides that best means to make an educated decision in the early stages of vehicle development.

- Confusion arose concerning the source of system mission performance information needed for the process. Some panel members and those in attendance at the session wrongly surmised that the MCA tool would provide characteristics and metrics to guide morphing vehicle development. The MCA tool was not intended to identify desirable characteristics or metrics for morphing, but only to assess those characteristics and metrics incorporated into a specific vehicle being evaluated.
- Some panel members and session attendees appeared confused as to whether the MCA process is a morphing system assessment tool or an aircraft mission performance assessment tool. The MCA tool was formulated to assess and compare how morphing systems perform a specific mission and to evaluate the technologies and risks associated with adding these capabilities. The mission performance analysis would still need to be performed using traditional means, and the output from this analysis would have to be supplied to the MCA tool.
- Questions were asked about how the process would handle a "system-of-systems" morphing concept involving multiple aircraft since the current process addresses only a single aircraft (i.e., is "platform-centric").
- The use of QFD analysis to assess vehicle and program risk was also questioned. Among the suggestions was that research into whether relevant information could be assumed or collected early in a project to assess the risk of new capabilities and technologies accurately.

Based on the industry panelist comments, it appears that there is little to no interest on their part to participate in the further development of an MCA process.

V. SUMMARY AND CONCLUDING REMARKS

This report presents a proposed structure and process for performing a morphing capability assessment. The impetus behind developing this framework is to help technologists, system developers, and PMs better discern and track the development of morphing vehicle technologies. The proposed framework consists of two distinct but interconnected parts: the MCoA (Morphing Concept Assessment) tool and the MCDL (Morphing Capability Development Level) table.

The MCoA tool, in its current form, uses the knowledge of the desired mission and the QFD methodology to calculate three numbers that can be used to evaluate morphing “success” as it applies to a predetermined mission.

The MCDL table contains general morphing vehicle system features and the corresponding development stages envisioned to realize a complete morphing vehicle. It may also guide and track morphing capability developments. A preliminary example of an MCDL table for a general morphing air vehicle was presented. However, it still needs refinements to represent all the key features desired in morphing vehicles. Once this is accomplished, the MCDL table could support investment decisions for future R&D programs.

As mentioned by the panel members, some developments and clarifications are still needed for the MCA framework. Among the items that have been mentioned is a closer look at the weighted average calculation of the MIS to ensure that the weighted average fully captures the desirability of one morphing vehicle configuration over another. One suggestion has been to not only track the weighted average number, but also the straight MIS. The QFD analysis of risk has also been questioned and requires further research to assure potential users that enough information can be obtained to capture fully the risk associated with a new technology. The final area of further refinement is the MCDL table. While an MCDL table can and has been assembled for one aircraft example, developing a table that is general enough to cover the entire spectrum of morphing aircraft, much less a generic morphing vehicle, is a daunting and possibly impossible task.

While many potential pitfalls have been identified and addressed, the MCA components have not been complete and validated. Future efforts should include testing the MCA framework on more representative examples, perhaps the DARPA MAS designs and other concepts under development by agencies such as NASA or ONR. The process should also be tested on morphing vehicles (e.g., ships) that operate in other mediums (the sea), vehicles (e.g., amphibious landing craft) that operate across two mediums (sea and land),or systems of vehicles where the individual vehicle only has one capability but multiple vehicles working together have more capability than the sum of the group.

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GLOSSARY

Λ	sweep angle
λ	taper ratio
3-D	three-dimensional
AFTI	Advanced Fighter Technology Integration
AFWAL	Air Force's Wright Aeronautical Laboratories
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
AR	wing aspect ratio
ASC	Aeronautical Systems Center
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
CRP	Central Research Program
DARPA	Defense Advanced Research Projects Agency
DSO	Defense Sciences Office
IDA	Institute for Defense Analyses
IFRA	In-Flight Reconfigurable Aircraft
MAS	Morphing Air Structures
MAW	Mission Adaptive Wing
MCA	Morphing Capability Assessment
MCDL	Morphing Capability Development Level
MCL	Morphing Capability Level
MCoA	Morphing Concept Assessment
MCS	Morphing Capability Score

MIS	Mission Impact Score
MPI	Mission Performance Index
NASA	National Aeronautics and Space Administration
ONR	Office of Naval Research
PM	program manager
QFD	quality function deployment
R&D	research and development
RCS	radar cross section
rms	root-mean-square
S&T	science and technology
SDM	Structures, Structural Dynamics, and Materials
t/c	Thickness-to-cord ratio
TR	Technical Report
TRL	technology readiness level
UAV	unmanned aerial vehicle

APPENDIX A.

A FRAMEWORK FOR MORPHING CAPABILITY ASSESSMENT

A FRAMEWORK FOR MORPHING CAPABILITY ASSESSMENT

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ABSTRACT

This paper describes a framework and process for assessing vehicle morphing capability in the context of a desired mission scenario, vehicle performance needed to realize the mission, and the state changes and potential technology advancements required to enable that vehicle performance. The process is subdivided into two parts: Morphing Concept Assessment and Morphing Concept Development Levels. This process is applied to an air vehicle to illustrate its use. While the paper focuses on air vehicles, the framework is intended to be independent of vehicle operational media (e.g., air, water, land, space). Even though many aspects of the assessment process are subjective, it provides a common framework for identifying, discussing, and evaluating critical vehicle and technology issues. It also provides a foundation for development of vehicle and technology research and development programs.

INTRODUCTION AND BACKGROUND

During the past decade, the multidisciplinary field of smart materials and structures experienced rapid growth in terms of individual technologies and applications. The structures demonstrated in these research and development (R&D) programs utilized integrated sensors, actuators and controllers to achieve limited shape change in response to environmental and operational conditions. Although largely successful, the full potential of smart system capabilities was not realized and the concept of "morphing" was proposed to take the next step forward.

Morphing became thought of as a revolutionary concept to allow for development of improved and new air-vehicle mission capabilities. Such capabilities might include the ability to perform current, dissimilar missions with fewer vehicles or the ability to perform completely new missions. These new capabilities were to be achieved via large shape changes leading to superior and/or new vehicle performance characteristics relative to current aircraft. During several meetings and small workshops, the concept of morphing evolved beyond shape change as the only way a vehicle can adapt to changes in environmental and operational conditions. Science and technology (S&T) programs for the Services and the National Aeronautics and Space Administration (NASA) began to be revitalized by these new ideas.

To further capitalize on these recent developments, the Office of Naval Research (ONR) and Defense Advanced Research Projects Agency/Defense Sciences Office (DARPA/DSO) co-sponsored an In-Flight Reconfigurable Aircraft (IFRA) Workshop in December of 2002. The workshop brought together a multi-disciplinary team of government, university, and industry specialists to

- Establish a common vision and understanding of how morphing might benefit future military air vehicle capabilities
- Identify critical path technologies and analytical tools to achieve such new capabilities
- Draft a technology/tool maturation timeline with rough order of magnitude costs to achieve such new capabilities
- Determine potential areas for coordination and leveraging of S&T investments based on current efforts and technology readiness levels [1]

The workshop focused solely on vehicle shape change for fixed-wing air vehicles up to high subsonic flight conditions.

In order to achieve the workshop objectives, a clear and consistent definition of morphing was required. While there are many definitions of "morphing" in use today, for the workshop and in this paper, "morphing" is defined as a capability to provide superior and/or new vehicle system performance by tailoring the vehicle's state to adapt to the environment and multi-variable mission roles, where:

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** Research Staff Member
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- Performance includes agility/maneuverability, range, speed, acceleration, radar cross-section, payload/weapons and sensors, etc.
- Vehicle state includes physical geometry/configuration, mechanical properties, electromagnetic properties, etc.
- Environment includes external operational conditions such as temperature, humidity, shock, vibration, electromagnetic, etc.

During the IFRA workshop planning, the need to develop metrics, a method to assess morphing capabilities, and a means to represent the assessment information was identified. Initial morphing capability assessment method development efforts were based in part on the Air Force's approach to develop autonomous unmanned aerial vehicle (UAV) control intelligence metrics[2]. The intent was, and still is, to develop a framework to assess morphing capabilities to aid in program planning and in tracking advancement of morphing R&D projects. The work presented in this paper is the result of the on-going effort to develop a framework for a "Morphing Capability Assessment" (MCA) tool/process.

The establishment of a general morphing capability assessment method is a desirable long-term goal and could prove useful to program managers, system developers, and science and technology researchers. As morphing vehicle and technologies R&D efforts continue, ideas and information need to be communicated effectively and efforts need to be coordinated across organizations. This need to plan and coordinate R&D efforts has helped motivate the development of a morphing capability assessment framework.

Currently, there are many approaches used to convey the potential impact of developing morphing aircraft and technologies on mission capabilities. Consequently, comparing and contrasting morphing vehicle and technology programs is challenging. Moreover, morphing capability should not be limited to air vehicles. Conceptually, vehicles operating in any environment (i.e., air, land, water, space) or any combination thereof may morph to achieve desired vehicle attributes or *states*. As the types of potential morphing vehicles and perceived required technologies increase, assessing the impact of morphing on capabilities and identifying technical needs will become more difficult.

Since most current morphing efforts are focused on air vehicles and technologies, this paper applies the proposed morphing capability assessment tool to air vehicles. However, the proposed framework is general enough to address vehicles operating in different media. Based on the definition stated previously, a morphing capability assessment process should systematically consider the vehicle's ability to effectively complete a desired mission based on changes in vehicle performance. Also, technology advancements that enable one or more vehicle components to change the vehicle's state leading to desired performance changes should be assessed in a self-consistent manner.

PROPOSED MORPHING CAPABILITY ASSESSMENT PROCESS

Developing a MCA process is a complex task and the connection between each of the following areas must be represented in a self-consistent and useful manner:

- Mission capabilities and required vehicle performance characteristics;
- Performance characteristic changes and vehicle state changes;
- Vehicle state changes and technology advancements.

At the end, the complete framework should support the selection of directions for morphing developments based on understanding the links among new mission capabilities, system performance changes, system state changes, and enabling technologies. The proposed MCA process is composed of two main parts: (i) the Morphing Concept Assessment (MCoA) process and (ii) the Morphing Concept Development Levels (MCDL) chart.

Morphing Concept Assessment (MCoA)

The MCoA process begins with the premise that a given mission has been conceived and ends with an assessment of different potential morphing solutions and related technologies required to accomplish it.

There are three very distinct but intimately related steps in the MCoA process, as shown in Figure 1. In the first step, the relationship between mission scenarios and required vehicle performance metrics is established. Generally, mission scenarios developed by the users will identify key vehicle performance characteristics required to accomplish those scenarios. The connection between the performance parameters of either existing or proposed vehicle and mission-defined key vehicle performance characteristics is represented on a performance-space "spider plot", as schematically illustrated in Figure 2. This plot allows comparison among performance characteristics of current, newly proposed, and/or envisioned vehicles. It also provides a clear illustration of advancements needed in vehicle performance to actually fulfill the mission. It should be expected here that new mission-defined vehicle performance characteristics would contain contradictory requirements relative to current vehicle capabilities, e.g., combining long endurance and high dash speed requirements in case of an aircraft, so that feasible solutions can only be achieved by significant vehicle state changes.

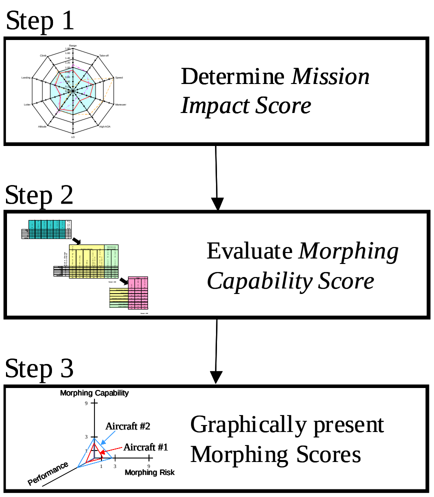
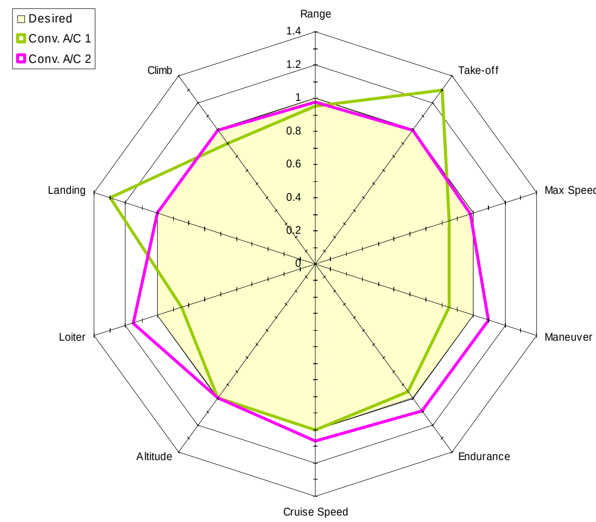


Figure 1—Three basic steps of the MCoA framework

Using the information from the performance space, a compound number can be determined that represents the *Mission Impact Score (MIS)* for the given vehicle (indicated in the table at the bottom of the spider chart—Figure 2). The MIS can be determined based on different combinations of normalized performance parameters, e.g., simple mean, geometric mean, root-mean-square, weighted mean, etc. Advantages and shortcomings of some of these means are discussed in the example section.

The defined performance parameters must be related to vehicle state changes, the means to achieve such changes, the enabling technologies available/to be developed, and their corresponding technology development risks (including costs). These result in four sub-steps that make up the core of the second step in the MCoA process. The process was developed based on a modified Quality Functional Deployment (QFD) approach.

Figure 3 illustrates the four sub-steps. First, the sensitivity of different state change parameters is mapped against key performance metrics determined from the MCoA Step 1. For this, already existing and new design tools are required that can perform the trade offs between morphing features. In the aircraft example, this reflects how wing area, aspect ratio, camber, etc. can affect vehicle performance parameters such as loiter time, range, dash speed, etc. At the end of this sub-step, the most effective state change parameters are ranked. Using these, morphing methods/schemes that can achieve those state changes are measured for effectiveness in performing the desired changes. These state changes can then be related to/linked to appropriate technologies necessary to achieve the required state changes. The fourth sub-step uses the selected state changes/technology pairs for a risk assessment based on cost, complexity, manufacturability, maintainability, etc. Finally, a compound number, denoted *Morphing Capability Score*, is obtained. Procedures to reduce the effect of individual bias to this measure and its detailed definition will be discussed in the following section.



	Desired	Aircraft # 1 Ratio	Aircraft # 2 Ratio	Weights
Range	4000	0.95	0.98	1.750
Take-off	3500	1.30	1.00	0.200
Max Speed	950	0.85	0.98	1.000
Maneuver	6.00	0.85	1.10	1.250
Endurance	5.00	0.95	1.10	1.500
Cruise Speed	0.75	1.00	1.07	1.000
Altitude	65000	1.00	1.00	1.000
Loiter	4.00	0.85	1.15	1.750
Landing	4500	1.30	1.00	0.200
Climb	5000	0.90	1.00	0.350

	Median	Sum	**Average**	Weighted
Aircraft # 1	**0.95**	**9.95**	**1.00**	**0.93**
Aircraft # 2	**1.00**	**10.37**	**1.04**	**1.05**

Figure 2—MCoA Step 1: determination of the *Mission Impact Index*

A graphical way of presenting the relative morphing capability of the compared vehicles and technologies is shown in Figure 4. For MCoA Step 3, the three morphing scores; the Morphing Performance Impact, the Morphing Capability Score, and the Morphing Risk Indicator; are plotted on a three-axis graph shown.

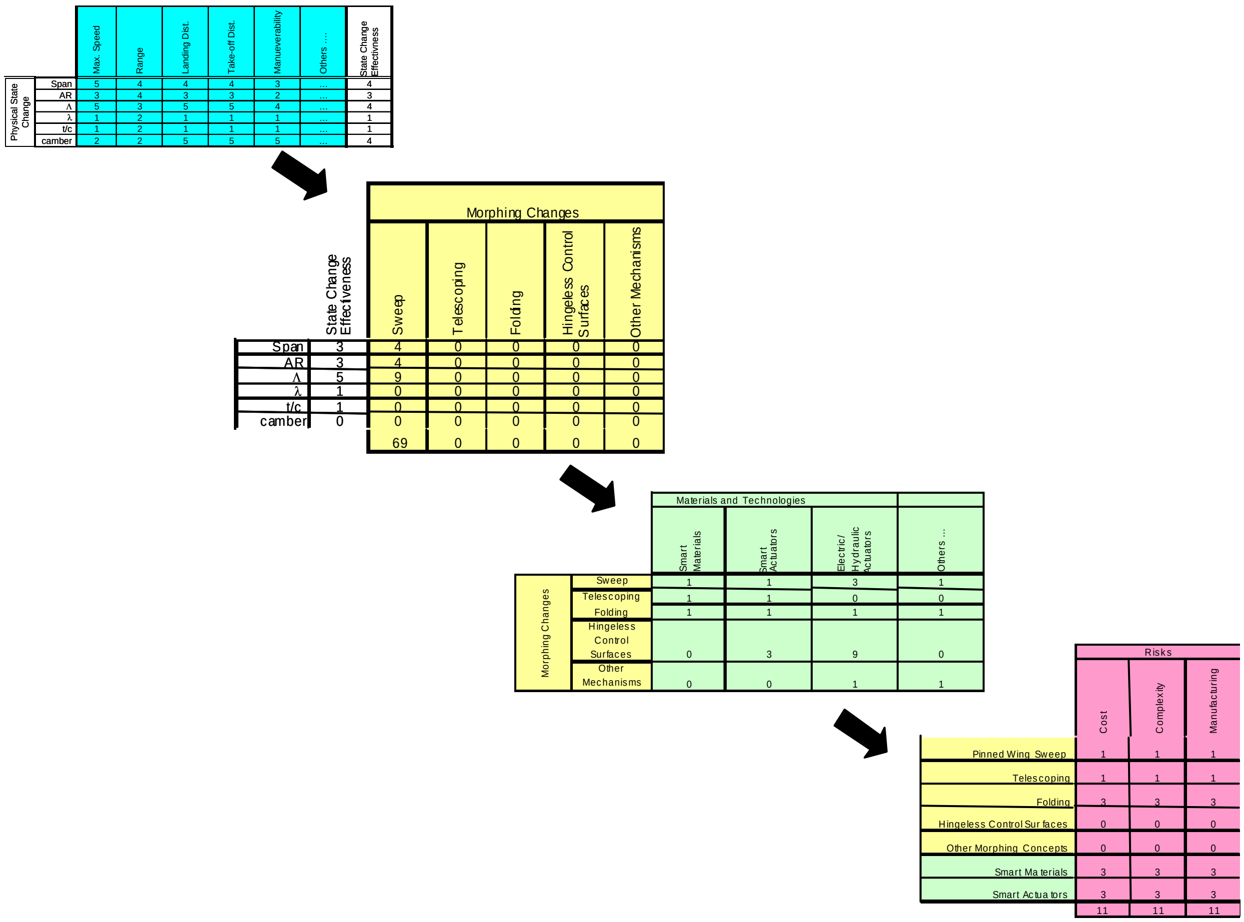


Figure 3—MCoA Step 2: determination of the *Morphing Capability Score*

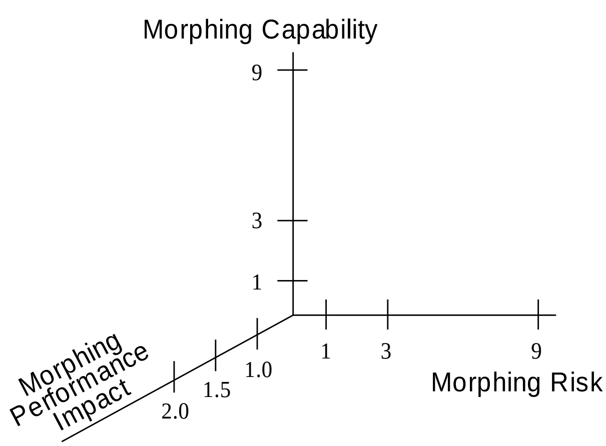


Figure 4—Plot representation used in Step 3 of MCoA

Example on the Usage of MCA

To illustrate the proposed assessment process, consider that an advanced aircraft designed to perform a strike/attack mission is sought (a type of mission that might have been desirable in the 1970's). The objective is to accomplish an existing mission (i.e., strike/attack) with improved effectiveness (e.g., deeper strike range, extended time on station, and increased vehicle maneuverability).

A set of performance metrics that a potential new aircraft must fulfill is derived from the mission requirements. Table 1 summarizes the mission performance metrics for this example.

Consider two notional aircraft as contenders to enable this new mission. Aircraft #1 is a supersonic, fighter/attack aircraft (with features similar to the General Dynamics F-111). Aircraft #2 is another fighter/attack aircraft similar to Aircraft #1 but with a particular morphing feature. (This second aircraft is based on the F-111 Mission Adaptive Wing airplane from the Advanced Fighter Technology Integration (AFTI) program. The AFTI F-111 aircraft advanced leading and trailing edge control surfaces[3] to actively control wing shape to improve flight performance.) Both aircraft have variable sweep wings. Aircraft #2 has adaptive leading and trailing edge control surfaces that allow smooth variable camber wings and contain the control system required to adjust the wing in response to different flight conditions. The conventional control surfaces on each wing are replaced by gapless surfaces that allowed the wing shape of Aircraft #2 to be optimized for landing, cruise, and high speed dash. As an example, Figure 5 shows how the AFTI F-111 wing shape changed for different lift versus drag requirements. While not an example of a vehicle with comprehensive morphing capabilities, it provides an initial test case to demonstrate the utilization of the MCA process.

Considering first the MCoA, the three steps to be applied to this example can be summarized as:

Step 1. Assess Vehicle Performance

Step 2. Determine Morphing Capability Score and Risk

Step 3. Graph Morphing Scores

After translating the mission into desired performance metrics, the first step in the proposed MCoA process is to determine how well the vehicles under consideration, in our case Aircraft # 1 and #2, perform against those metrics. Because most of the principal metrics have different units, a normalized ratio of the vehicle performance parameter relative to the desired performance is made. The individual aircraft ratios are then plotted on a spider plot (Figure 6) against the desired mission performance characteristics. The table under the plot shows the given mission performance characteristics and the resulting ratio for Aircraft # 1 and Aircraft #2. As may be seen from the plot, Aircraft #2 improves on the performance achieved by Aircraft # 1 with respect to range, loiter time, and maximum speed, and, in some cases, greatly outperforms it for the given mission metric.

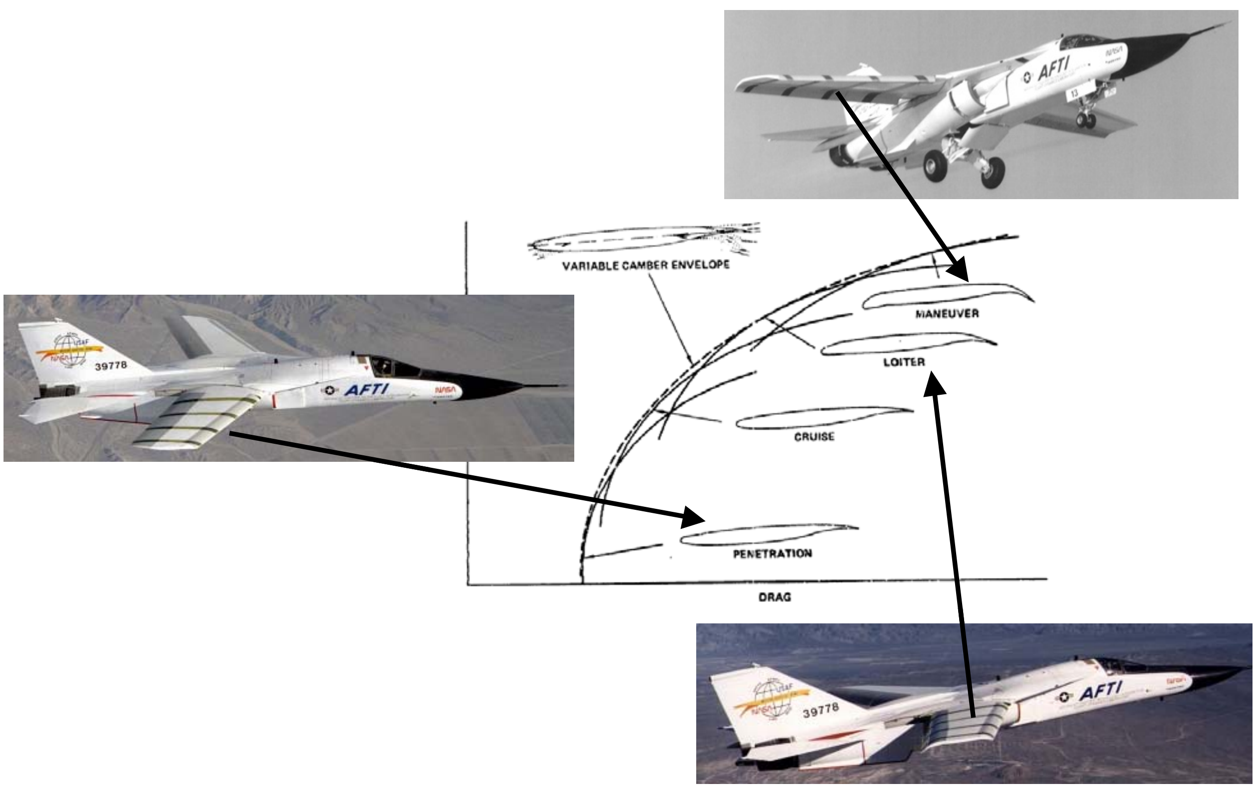


Figure 5—Description of AFTI F-111

Table 1. Desired Attack/Loiter Mission Performance Metrics

Mission Performance Parameters	Desired Value
Range (NM)	4,000
Take-off Distance (ft)	3,500
Maximum Speed (knots)	950
Maneuver Limit (g's)	6
Endurance (hr)	5
Cruise Mach No.	0.75
Maximum Altitude (ft)	65,000
Loiter Time (hr)	4
Landing Distance (ft)	4,500
Climb Rate (ft/sec)	5,000

To arrive at the Mission Performance Impact score, the vehicle score that describes how the aircraft performs the given mission, a weighted average can be used for the performance ratios. For the example chosen, both a simple average and a weighted average calculation were done to show why the weighted average is currently the preferred method to calculate MPI. If a simple average is used, the MPI for Aircraft #2 is 1.04 while that for Aircraft #1 is 1.00. What these numbers imply is that Aircraft #2 would outperform, on the whole, the desired mission performance goals by 4% while Aircraft #1 meets the desired mission performance criteria. While a well-selected set of performance metrics characterizes the desired mission, not all metrics have the same mission impact. In fact, the MPI score can be skewed because one performance metric is greatly different from what is required. To address this issue, a weighted average function is used to ensure the mission performance metrics that are most critical count the most towards the MPI score. To determine the weights, the evaluator assigns an importance or weight to each metric by setting the higher weights for attributes that are significant and reducing the weight for less important ones. A numerical example of how the standard average calculation can misinterpret the relative performance effectiveness of each aircraft is shown in the two left columns in the table of Figure 6.

It is assumed for this strike/attack mission that the range of the aircraft is a much more important metric than the takeoff and/or landing distances (within reason). This is reflected in the choice of weights: 1.75 for range and 0.20 for takeoff/landing distance. The rankings show that if simple average were used to calculate MPI, Aircraft #1 and #2 would be rated very closely. This is not a true reflection of each aircraft's ability to meet the define mission scenario. Using the weighted average, on the other hand, gives Aircraft #2 the higher MPI value, 1.05 versus 0.93 for Aircraft #1. The higher MPI indicates that Aircraft #2 better satisfies the performance metrics that represent the desired mission. It clearly scores higher in the categories that were deemed more important, and, therefore, assigned higher weights: range, loiter, endurance and maneuver capability for this particular example.

Step 2 in the MCoA provides information on what physical characteristics are necessary and what technologies may be applied to achieve the performance results of Step 1. As previously described, Step 2 applies a modified QFD process to the morphing vehicles to discern the benefits and risks associated with incorporation of different morphing technologies. The QFD process was developed originally to help multidisciplinary organizations focus on customer requirements[4]. The qualities important in identifying customer needs, namely non-evenly distributed scoring to differentiate between "low-medium-high" impact, technology identification, and relative importance recognition, are the same as those necessary to quantify morphing capability.

For this example, a three-step QFD analysis is applied. The first part involves determining the effectiveness of selected state changes on individual performance metrics; this was established in Step 1, and is, therefore, linked directly to the mission effectiveness. Values from 1 (lowest) to 5 (highest) are used to quantify the impact. For the current example, physical characteristics that could be changed by morphing the wing are the wing span, wing aspect ratio (AR), sweep angle (Λ), taper ratio (λ), wing thickness-to-chord ratio (t/c), and wing camber. The scores for each physical state are determined through a combination of numerical simulations, knowledge of the morphing vehicle being evaluated, and an understanding of how the physical changes affect each of the selected performance metrics. This is summarized in Figure. 7. The simple average of the scores for each state change effectiveness rating (right column in Figure 7) will be used as the weight in the calculation of the Morphing Capability Score. For Aircraft #1 and #2, the span change, sweep angle, and camber change were rated high and given average scores of 4. Taper ratio and thickness-to-chord ratio were not as important to the given mission and were rated only as 1, the lowest value. The average of these values are then placed in the left most column of the QFD matrix for Part 2 (see Figure 8).

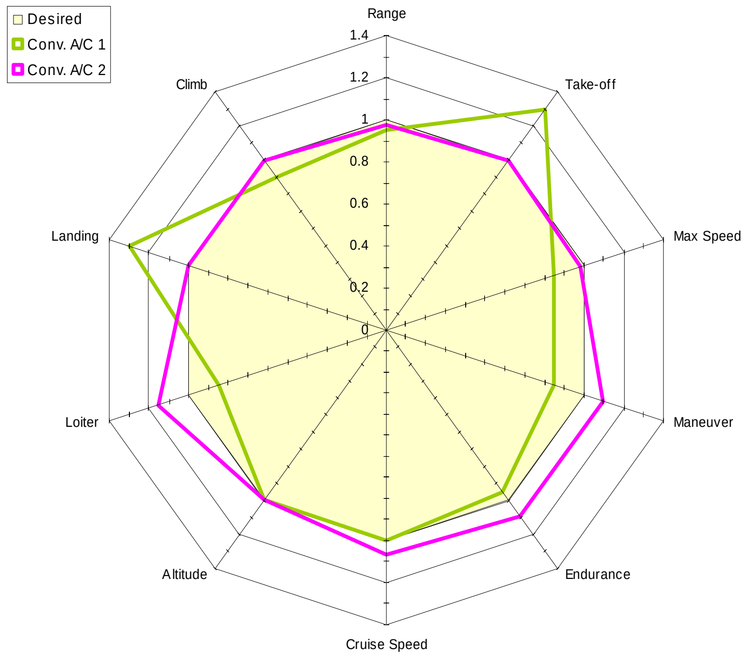


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Figure 6—MCoA Step 1: Vehicle performance metrics

The next step represents the connection between morphing methods and technologies to the physical state changes. This is illustrated in Figure 8 for both example aircraft. The means and methods used to achieve morphing are placed in the vertical columns and scored with a 0, 1, 3, or 9 depending on whether they make zero, small, moderate, or large contributions to the physical state change of the vehicle. Returning to the example, Aircraft #1 and Aircraft #2 share a common characteristic, namely a variable sweep wing. Aircraft #2, though, varied from #1 in that it has variable camber leading and trailing edge control surfaces that could be used to more precisely tailor the wing shape for landing, take-off, cruise, and dash. This difference is reflected in the "Hingeless Control Surface" column, where the value is zero for Aircraft #1 and 9 for the Aircraft #2. The capability score given to each aircraft is a normalized average with the normalizing value being 9 times the number of non-zero boxes in the QFD matrix, i.e., the maximum score possible. As the scores show, Aircraft #2 receives a higher MCS. This was expected due to the inclusion of the highly adaptive leading and trailing edge control surfaces. As morphing capabilities and use of smart structures increase, the MCS scores will rise above the "low" value seen in this example.

Physical State Change		Max. Speed	Range	Landing Dist.	Take-off Dist.	Manueverability	Others	State Change Effectivness
	Span	5	4	4	4	3	...	4
	AR	3	4	3	3	2	...	3
	Λ	5	3	5	5	4	...	4
	λ	1	2	1	1	1	...	1
	t/c	1	2	1	1	1	...	1
	camber	2	2	5	5	5	...	4

Figure 7—MCoA Step 2/Part 1: Mission impact assessment of selected physical state changes

While knowing that an aircraft has a higher morphing capability is important, an assessment of the risk in development and operations would also provide much needed information to the program manager selecting which concept to fund or to system developers seeking to identify risk early in a program. This is the core of Part 3 of the MCoA process. The risk assessment is done using a similar QFD approach to that in Part 2. For the risk assessment, the items of interest, i.e., mechanisms and technologies, are placed in the left column as shown in Figure 9. They are compared to areas of risk including but not limited to cost, schedule, and manufacturing. The columns are then multiplied together, summed, and the normalized average is determined (as in Part 2) to arrive at the risk score. As would be expected for the aircraft selected in our example, Aircraft #2 showed a much higher risk score than Aircraft #1 due to the variable leading and trailing edges. The higher risk does not necessarily mean that the project is not warranted, only that there are aspects of the cost, complexity, schedule, and/or manufacturing that require attention and vigilance to reach successful completion. The risk analysis portion of the MCA framework is meant to identify technology areas that require extra attention.

			Morphing Methods					Materials and Technologies		
		State Change Effectivness	Pinned Wing Sweep	Telescoping	Folding	Hingeless Control Surfaces	Other Morphing Concepts	Smart Materials	Smart Actuators	Other Technologies
Physical State Change	Span	4	3	0	0	0	0	1	1	...
	AR	3	3	0	0	0	0	1	1	...
	Λ	4	9	0	0	0	0	1	1	...
	λ	1	0	0	0	0	0	0	0	...
	t/c	1	0	0	0	0	0	0	0	...
	camber	4	0	0	0	0	0	1	1	...
			57	0	0	0	0	12	12	...

Overall Score **81**
Capability Score **0.8**

Aircraft #1

			Morphing Methods					Materials and Technologies		
		State Change Effectivness	Pinned Wing Sweep	Telescoping	Conventional, Hinged Trailing Edge Control Surfaces	Hingeless Control Surfaces	Other Morphing Concepts	Smart Materials	Smart Actuators	Other Technologies
Physical State Change	Span	4	3	0	0	0	0	1	1	...
	AR	3	3	0	0	0	0	1	1	...
	Λ	4	9	0	0	0	0	1	1	...
	λ	1	0	0	0	0	0	0	0	...
	t/c	1	0	0	0	0	0	0	0	...
	camber	4	0	0	0	9	0	1	1	...
			57	0	0	36	0	15	15	...

Overall Score **123**
Capability Score **1.1**

Aircraft #2

Figure 8—MCoA Step 2/Part 2: Connecting morphing methods and technologies to state changes

Step 3 in the MCoA process is simply plotting the relative scores from the three previous steps onto a three-axes plot, Figure 10. One axis is the mission performance impact (MPI), another the morphing capability score (MCS), and the third is a measure of the risk assessment. This plot allows a graphical comparison of each vehicle in terms of its performance, morphing capability, and risk for a desired mission. Initially, the goal of the MCoA tool was to arrive at a single number that could be used to rank morphing concepts. With continuing development of this assessment process, it has become clear that one number provides little information in terms of assessing performance benefits, morphing ability, or risk associated with morphing concepts. In lieu of this single number, the graphical representation shows how the vehicles compare in the three critical areas.

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Folding	0	0	0
Hingeless Control Surfaces	0	0	0
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Smart Actuators	1	1	1
	5	5	3

Risk Score **1.08**

Aircraft #1

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Folding	0	0	0
Hingeless Control Surfaces	3	9	3
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Smart Actuators	1	1	1
	8	14	6

Risk Score **2.33**

Aircraft #2

Figure 9—MCoA Step 2/Part 3: Risk assessment

To help make the comparison between vehicles easier, the plots can be unfolded and the projection of each side of the triangle plotted. The projection plots are shown in Figure 11. The projection plots may be especially useful during technology development phases for which adequate information may not be readily available to complete the entire assessment. As can be seen from Figures 11 and 12, Aircraft #2 scores higher in all the categories including risk.

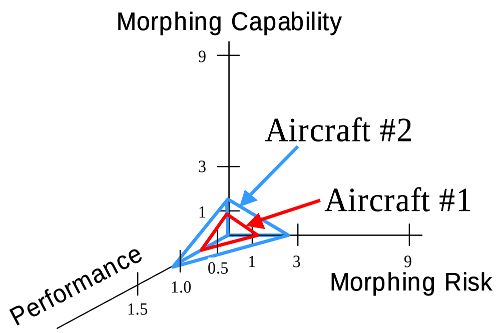

Figure 10—MCoA Step 3: Comparison of different morphing concepts

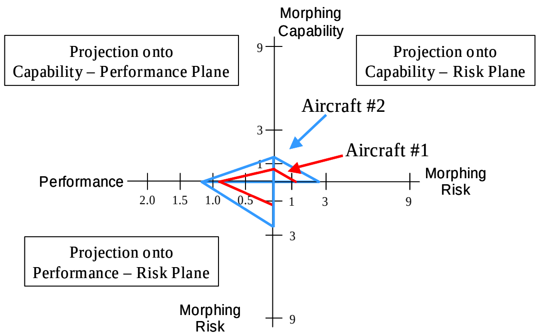

Figure 11—Projection plots for morphing capability of the different vehicles

Morphing Concept Development Levels (MCDL)

While the MCoA tool provides the ability to assess proposed vehicle and technology concepts relative to achieving desired mission capabilities, the MCDL chart is intended to provide a broader, qualitative view of morphing capabilities *and* goals for future vehicle systems. It must present the progression of key attributes to a final set of desired features based on the morphing vehicle system objectives. These objectives must be set *a priori* as a reflection of a long-term vision on morphing development. Thus, the MCDL could serve as a program-planning tool to indicate general directions and goals for technology and vehicle system morphing capability advancement.

The vehicle system attributes to be considered in the MCDL are grouped in two sets of features: vehicle type-independent and vehicle specific. Figure 12 presents an initial representation of such chart and its feature development phases. In this particular case, the vehicle specific features are considered for an air vehicle. Ranging from no special feature to a full morphing realization, each feature stream (column) is subdivided in ten levels.

The vehicle independent features describe desired characteristics of a vehicle independent of its operational environment (i.e., air, water, land, space, or some combination of them). The mission effectiveness column captures the desire to perform existing missions and combinations of existing missions, as well as to enable new missions. It is also desired that the vehicle present great adaptability to the environment and threats. Since the focus to achieve these features is through state changes, the morphing development should progress in such a way that will eventually lead to large state changes. Finally, overall cost assessment of the methods employed in the morphing realization, from component to the system level, must be such that it provides great improvements over existing methods.

The vehicle specific part of the MCDL chart is much more complex to establish. It involves the identification of key features that characterize the vehicle class (i.e., operational media) under consideration. Once such characteristics are defined, envisioned phases of development ranging from those requiring no special features to those required for a complete morphing vehicle must be developed for each of those key features. As a first attempt to identify some of these key features and their envisioned developmental stages towards a complete morphing air vehicle, three specific features are proposed: lift generation surfaces, means of maneuvering (represented in the chart under the column "Maneuvering Capability"),, and survivability/ maintainability, particularly during flight operations. Inspired in biological systems, the desired morphing aircraft would conformably deploy lifting surfaces, provide high-bandwidth maneuver forces and moments, and present adaptability/maintainability on demand. These vehicle-specific streams are very important to help guide the research investment for development of specific features associated with a vehicle being operated in given media. In contrast, the vehicle independent features are what ultimately need to be present in a new system that will satisfy the stated needs

To aid in general program planning, it is essential that morphing concepts be assessed in terms of a high-level vision of the desired features of the weapon system. Consider the MCDL chart presented in Figure 12 as an initial representation of that high-level vision. In the context of the example above, Aircraft #2 presents certain key vehicle features that can be mapped into the MCDL chart. These are shown by the dashed dots and lines in Figure 12. The advanced strike/attack mission can be seen as a level 3 under "Mission Effectiveness." Similarly, the camber changes are reflected as small state changes in the context of morphing state changes. Although the extra maneuverability provided by the small reshaping of the wing increases its survivability, the vehicle provides minimum adaptability to the environment and/or threats, reflecting in a level 2 score in the corresponding column in the MCDL chart.

	Vehicle-independent Features				Vehicle-specific Features		
Level	Mission Effectiveness	State Change/Efficiency	Adaptability to Environment and/or Threat	Generalized Cost ($, weight, complexity, power, reliability)	Lift Generation Surfaces	Maneuvering Capability	Survivability/Maintainability
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat- cannot be done with other methods	Great improvement over existing methods - from component to system levels	Conformally deployed liftting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability/maintainability on demand
9	Enable new mission with improved effectiveness	Large state change - competes with existing methods	Great adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level			Self-healing systems
8	Enable new mission	Large state change - inefficiently replaces existing methods	Great adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the weapon system level		Conformally deployed control surfaces from wing-fuselage	
7	Combining (dissimilar) existing missions with superior effectiveness	Moderate state change - exceeds performance of existing methods	Moderate adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon system level			
6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
5	Combining (dissimilar) existing missions inefficiently	Moderate state change - inefficiently replaces existing methods	Moderate adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the vehicle level	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Aircraf re-trimming after failure/damage, store/load changes, etc.
4	Perform existing missions with superior effectiveness	Minimal state change - exceeds performance of existing methods	Minimal adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the vehicle level	Conformal lifting surfaces sweep and/or surface area change	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw	Vehicle real-time reconfigurable flight envelop based on usage and health monitoring information
3	Perform existing missions with improved effectiveness	Minimal state change - competes with existing methods	Provides minimal adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the component level	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes for secondary flight controls; increase maneuverability and decrease vulnerability	In-flight active loads re-distribution
2	Perform existing missions with current effectiveness	Minimal state change - inefficiently replaces existing methods	Provides minimal adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the component level	Discrete lifting surface sweep and/or area change	Conformal lifting surface changes driven by discrete surfaces	Vehicle usage and health monitoring
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features	No special features

Figure 12— Morphing Concept Development Levels (with specific features for morphing air vehicles)—dashed lines indicate key features as being captured by Aircraft #2

Considering that the physical realization of the camber change mechanisms for Aircraft #2 follows the one used in the AFTI F-111, the additional mechanical complexity and potential weight penalty will have a negative impact on generalized costs. This would be indicated in Figure 12 as a level 1 score. In terms of vehicle-specific features, Aircraft #2 does provide an advance on the lift generation surface features, thereby achieving level 3 due to the presence of airfoil shape change associated with camber deformation. This also provides an increase in maneuverability and changes in secondary flight controls through adjusting the wing shape through different mission segments. Finally, Aircraft #2 does not present any special feature for improved maintainability or survivability.

With these results, if the Aircraft #2 concept goes forward and is developed, progress will be made in certain features that support the morphing objectives (as indicated in the MCDL chart, Figure 12). On the other hand, such a program will not address certain key features that will be part of a complete morphing aircraft and new development programs in those areas will be necessary to attain the complete morphing objectives. By representing different programs using this common framework and process, program managers and researchers will see which features are being developed and which ones are lagging and need more attention. In the example above, that may drive the funding allocation for new programs to issues associated with integrated vehicle health management systems, as a next step towards further development on survivability/ maintainability (since this is still at level 1 in Figure 12).

CONCLUDING REMARKS

This paper presents a proposed structure and process for performing a morphing capability assessment. The impetus behind developing this framework is to help technologists, system developers, and program managers to better discern and track the development of morphing vehicle technologies. The proposed framework consists of two distinct but interconnected parts: the Morphing Concept Assessment tool and the Morphing Concept Development Level chart.

The MCoA tool, in its current form, utilizes knowledge of the desired mission and the quality functional deployment tool methodology to calculate three numbers that can be used to evaluate morphing "success" as it applies to a pre-determined mission.

The MCDL chart contains general morphing vehicle system features and the corresponding envisioned development stages towards realization of a complete morphing vehicle realization. It may also guide and track morphing capability developments. A preliminary example of a MCDL chart for a general morphing air vehicle was presented. However, it still needs further refinements to represent all the key features desired in morphing vehicles. Once this is accomplished, the MCDL chart could support investment decisions for future R&D programs.

While many potential pit-falls have been identified and addressed, the MCA components are not complete and validated, and future efforts should include testing the MCA framework on more representative examples, perhaps the DARPA Morphing Aircraft Structures (MAS) designs and other concepts under development by agencies such as NASA or ONR.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Terry Weisshaar of DARPA, Mr. Bill Horn of NavAir, and Dr. Yevgeny Macheret and Dr. Janet Sater of the Institute for Defense Analyses for all their support and guidance during the development of the Morphing Capability Assessment process. The authors would like to especially thank Mr. Lawrence Ash of the Office of Naval Research, whose initial interest and energy was the driving force behind the development of this framework.

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APPENDIX B.
MCL PANEL DISCUSSION SESSION

Note for Appendix B: *The remainder of the pages in Appendix B are not numbered. The layouts of some of the slides prevented a page number from being added in a consistent location on all the pages. These pages do, however, appear, in the order in which they were presented at the April 2004 briefing.*

MCL Panel Discussion Session

Tuesday, 20 April 2004, 9:30-12:30

- Opening remarks
- Presentation of MCL Paper
- Panelist remarks
- Questions/comments from audience; discussion with Panel and authors

Rules of engagement for discussion

- Please clearly state name/affiliation
- Please feel free to criticize! But also provide specific constructive comments, with your alternative approaches/suggestions (non-proprietary).
- We will be documenting this discussion and plan to issue a follow-up report
  - Provide your business card if you want a copy, OR
  - Contact Janet Sater at “jsater@ida.org”.
- Thank you for your interest!

A Framework for Morphing Capability Assessment

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Department of Aerospace Engineering
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and
Christopher A. Martin
Science and Technology Division
Institute for Defense Analyses, Alexandria, Virginia

Presented at the
12th AIAA/ASME/AHS Adaptive Structures Conference
Palm Springs, California, 20 April 2004

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Overall Needs

- Need to provide direction for morphing development
- Need to establish a common understanding and framework to compare different solution options addressing morphing development
- Need to provide tracking of progress towards morphing capabilities

It is still very much a *work-in-progress* and needs the input of this community

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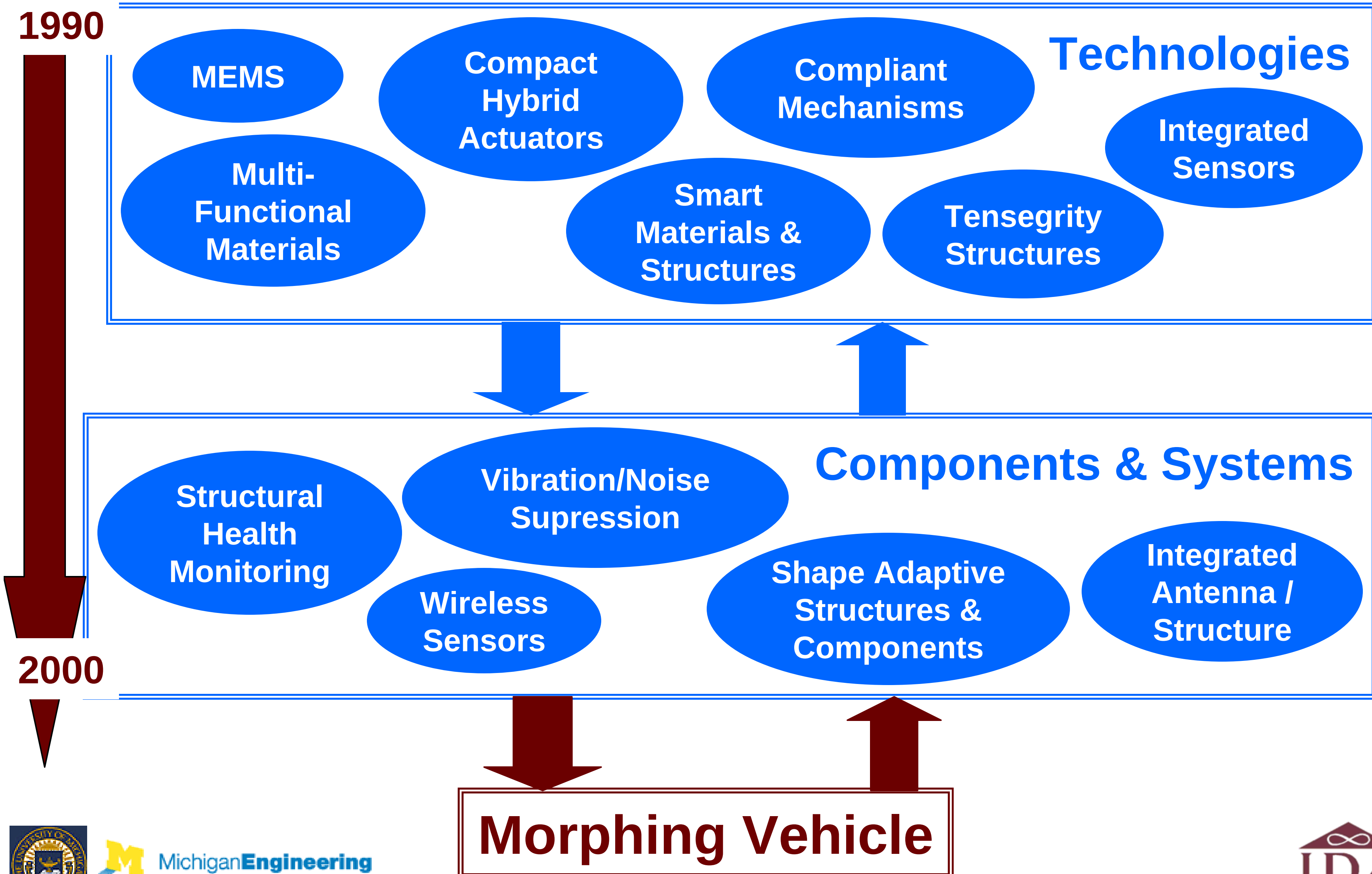
Outline

- Background
- Proposed Morphing Capability Assessment (MCA) process overview
  - Morphing Concept Assessment (MCoA)
  - Morphing Concept Development Levels (MCDL)
- Summary

‘Smart’ Technologies, Systems and Morphing



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Based on information from IDA Paper P-3552

Morphing Vehicle: Current Efforts

- DARPA Morphing Aircraft Structures program
- DARPA Compact Hybrid Actuator program (CHAP) Flight Demo
- NASA Morphing Program
- AFRL Air Vehicles Adaptive Structures projects
- AFRL Munitions Directorate programs
- Industrial R&D programs (SBIR & IRAD)
- University R&D programs

Observations (prior to Dec 2002)

- Many definitions of morphing existed
- Enabling technology and tool R&D occurring across several organizations, but not closely coordinated
- No process existed to aid researchers, S&T program planners and managers to make the connection between technologies/tool advancements and achieving reconfigurable aircraft with desired capabilities

In-Flight Reconfigurable Aircraft (IFRA) Workshop

- Co-sponsored by DARPA/DSO and DDR&E
- Held in December 2002
- Objectives:
  - Establish common vision & understanding of how morphing might benefit future military air vehicles
  - Identify critical path technologies and analytical tools needed
  - Draft a technology/tool maturation timeline with ROM costs to achieve such new capabilities
  - Determine potential areas for coordination and leveraging of S&T investments

IFRA Workshop – cont.

In order to achieve the workshop objectives, the organizers and sponsors realized that the following was needed:

- a common “morphing definition” to facilitate discussion & understanding, and
- a process or method to develop, in a consistent manner, an understanding of the impact of morphing and the needed technologies and tool advancements

Morphing Capability Assessment Process

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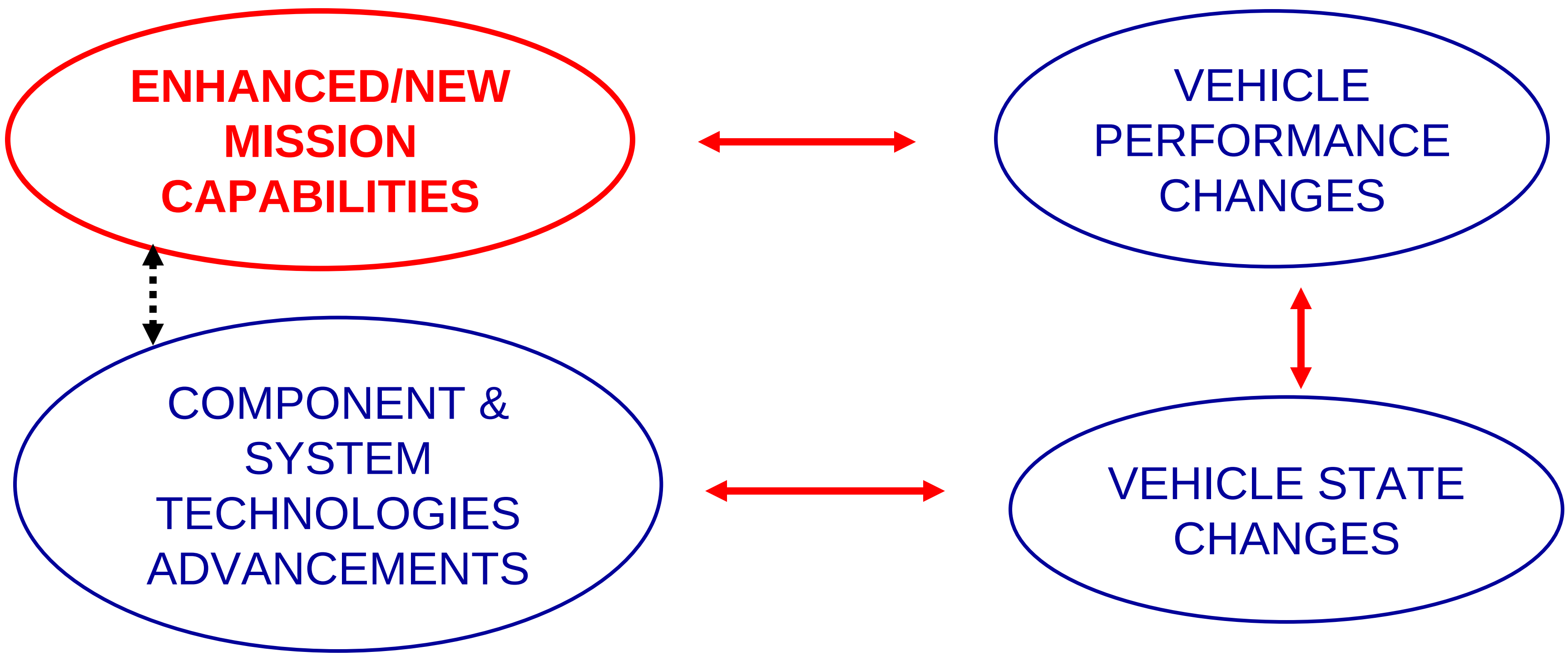
Morphing Definition

"Morphing is a capability to provide superior and/or new vehicle system ***performance*** in flight by tailoring the vehicle's ***state*** to adapt to the environment and multi-variable ***mission*** roles;

- performance includes agility/maneuverability, range, speed, acceleration, RCS, payload/weapons and sensors, etc.
- vehicle state include physical geometry/configuration, mechanical properties, electromagnetic properties, etc.
- environment includes atmospheric, electromagnetic, etc."

Why Develop a Morphing Capability Assessment (MCA) Process?

- Establish a common framework for the discussion of morphing capabilities in a self-consistent and useful manner
- Provide direction for morphing developments based on understanding the military needs and the links among:



- Track progress toward achieving morphing vehicle capabilities

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Proposed MCA process

Establish broader, long-term S&T goals for morphing vehicle development

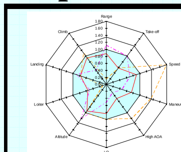
Morphing Concept Development Levels (MCDL) chart

Level	Mission Effectiveness	State Change/Efficiency	Adaptability to Environment and/or Threat	Generalized Cost ($, weight, complexity, power, reliability)	Lift Generation Surfaces	Maneuvering Capability
	Vehicle-independent Features				Vehicle-specific Features	
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat- cannot be done with other methods	Great improvement over existing methods - from component to system levels	Conformally deployed liftting surfaces on demand	High-bandwidth maneuver forces and moments on demand
9	Enable new mission with improved effectiveness	Large state change - competes with existing methods	Great adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level		
8	Enable new mission	Large state change - inefficiently replaces existing methods	Great adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the weapon system level		Conformally deployed control surfaces from wing-fuselage
7	Combining (dissimilar) existing missions with superior effectiveness	Moderate state change - exceeds performance of existing methods	Moderate adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon system level		
6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change	
5	Combining (dissimilar) existing missions inefficiently	Moderate state change - inefficiently replaces existing methods	Moderate adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the vehicle level	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes
4	Perform existing missions with superior effectiveness	Minimal state change - exceeds performance of existing methods	Minimal adaptability to environment and/or threat- cannot be done with other methods	Inneficient w.r.t. existing methods - at the vehicle level	Conformal lifting surfaces sweep and/or surface area change	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw
3	Perform existing missions with improved effectiveness	Minimal state change - competes with existing methods	Provides minimal adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the component level	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes for secondary flight controls; increase maneuverability and decrease vulnerability
2	Perform existing missions with current effectiveness	Minimal state change - inefficiently replaces existing methods	Provides minimal adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the component level	Discrete lifting surface sweep and/or area change	Conformal lifting surface changes driven by discrete surfaces
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features

Given desired mission, assess vehicle concepts/designs

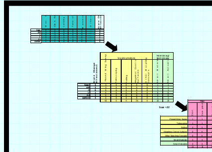
Morphing Concept Assessment (MCoA)

Step 1



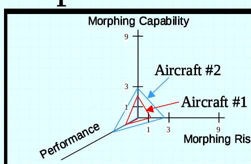
Determine *Mission Impact Score*

Step 2



Evaluate *Morphing Capability Score*

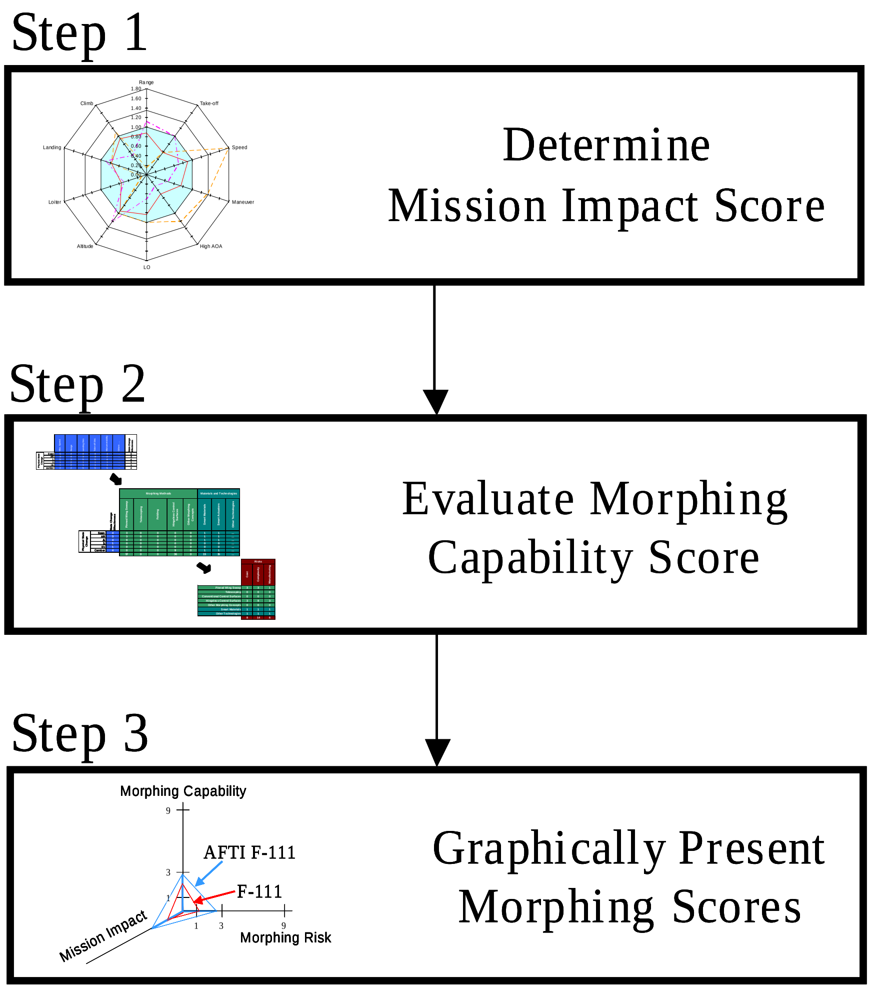
Step 3



Graphically present Morphing Scores

Current Process with Example

Basic Steps of MCoA Framework



- Step 1
  - Establish relationship between mission scenarios and vehicle performance
- Step 2
  - Relates performance parameters to vehicle changes and technologies through QFD process
- Step 3
  - Graphically represent Morphing Capability, Risk and Mission Impact Scores

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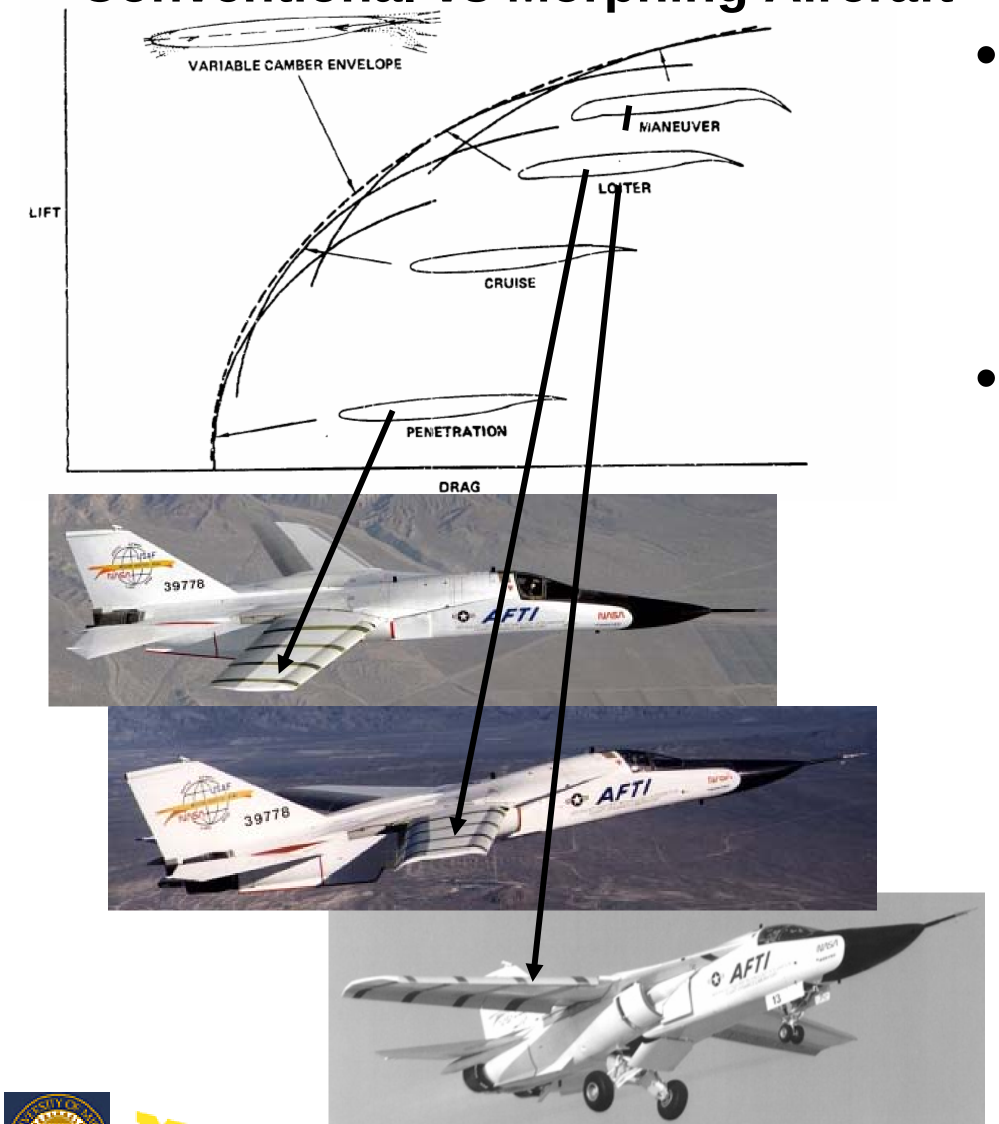
Required Inputs to MCA Process

- Step 0 – Vehicle Mission
  - Customer Provided
  - Defined mission required to initiate the MCA process
- Step 1 – Quantified Vehicle Performance
  - Developer Provided
- Step 2 – Technologies List for Vehicle
  - Developer Provided
- Various mixtures of mediums (air / water / ground) can be handled by current process
  - Not known whether process can be worked backwards to mission

Worked Example – Aircraft #1 and #2

Conventional vs Morphing Aircraft



- Aircraft #1
  - Variable sweep, supersonic fighter-bomber designed and built for fighter/attack missions
- Aircraft #2
  - Similar to Aircraft #1, but with adaptive leading and trailing edge control surfaces
  - Leading and trailing edge control surfaces similar to those developed for F-111 on Advanced Fighter Technology Integration (AFTI) program.

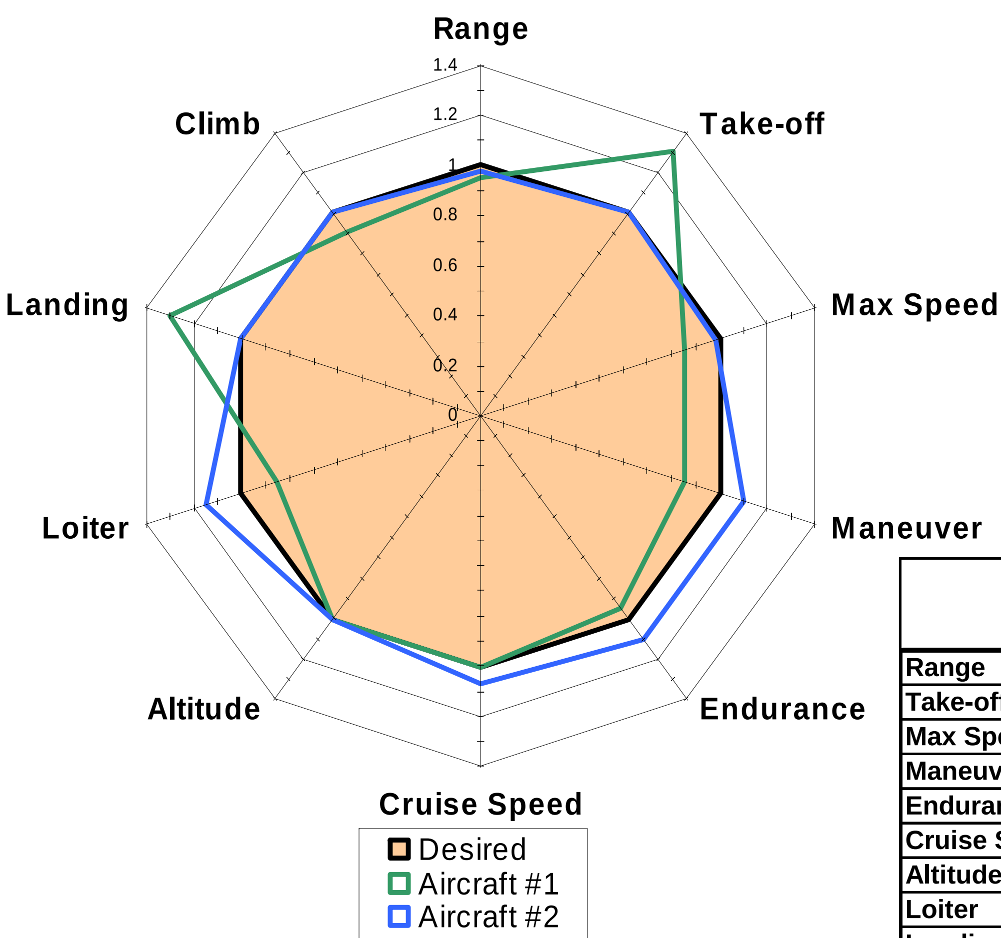
Step 0 – Key Mission Performance Metrics

Example Mission

Mission Performance Parameters	Desired Value
Range (NM)	4,000
Take-off Distance (ft)	3,500
Maximum Speed (knots)	950
Maneuver Limit (g's)	6
Endurance (hr)	5
Cruise Mach No.	0.75
Maximum Altitude (ft)	65,000
Loiter Time (hr)	4
Landing Distance (ft)	4,500
Climb Rate (ft/sec)	5,000

- Fighter/attack mission
  - Range: 4000 nmi
  - High speed dash
  - Significant loiter time
- Parameters chosen to stress conventional aircraft designs and highlight necessity for reconfigurable aircraft

Step 1 – Mission Impact Score



- Weighted average used to identify and focus analysis to “important” parameters
- Results
  - Aircraft #1 = 0.93
  - Aircraft #2 = 1.05

	Desired	Aircraft # 1 Ratio	Aircraft # 2 Ratio	Weights
Range	4000	0.95	0.98	1.750
Take-off	3500	1.30	1.00	0.200
Max Speed	950	0.85	0.98	1.000
Maneuver	6.00	0.85	1.10	1.250
Endurance	5.00	0.95	1.10	1.500
Cruise Speed	0.75	1.00	1.07	1.000
Altitude	65000	1.00	1.00	1.000
Loiter	4.00	0.85	1.15	1.750
Landing	4500	1.30	1.00	0.200
Climb	5000	0.90	1.00	0.350

	Median	Sum	Average	Weighted
Aircraft # 1	0.95	9.95	1.00	0.93
Aircraft # 2	1.00	10.37	1.04	1.05

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Step 2 – Morphing Capability Score

Physical State Change		Max. Speed	Range	Landing Dist.	Take-off Dist.	Manueverability	Others	State Change Effectivness
	Span	5	4	4	4	3	...	4
	AR	3	4	3	3	2	...	3
	Λ	5	3	5	5	4	...	4
	λ	1	2	1	1	1	...	1
	t/c	1	2	1	1	1	...	1
	camber	2	2	5	5	5	...	4

Part 1
State Change Effectiveness

Physical State Change		State Change Effectivness	Morphing Methods: Pinned Wing Sweep	Telescoping	Folding	Hingeless Control Surfaces	Other Morphing Concepts
	Span	4	3	0	0	0	0
	AR	3	3	0	0	0	0
	Λ	4	9	0	0	0	0
	λ	1	0	0	0	0	0
	t/c	1	0	0	0	0	0
	Camber	4	0	0	0	9	0
			57	0	0	36	0

Part 2
Morphing Capability Score

Physical State Change		State Change Effectivness	Materials and Technologies: Smart Materials	Smart Actuators	Other Technologies
	Span	4	1	1	...
	AR	3	1	1	...
	Λ	4	1	1	...
	λ	1	0	0	...
	t/c	1	0	0	...
	camber	4	1	1	...
			15	15	...

	Risks: Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Conventional Control Surfaces	0	0	0
Hingeless Control Surfaces	3	9	3
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Other Technologies	1	1	1
	8	14	6

Part 3
Morphing Risk Assessment

- Modified QFD assessment used
- Technologies (e.g., smart structures and materials or morphing methods) linked to vehicle feature being altered
- Risk (e.g., manufacturing, cost, etc.) also linked to technologies

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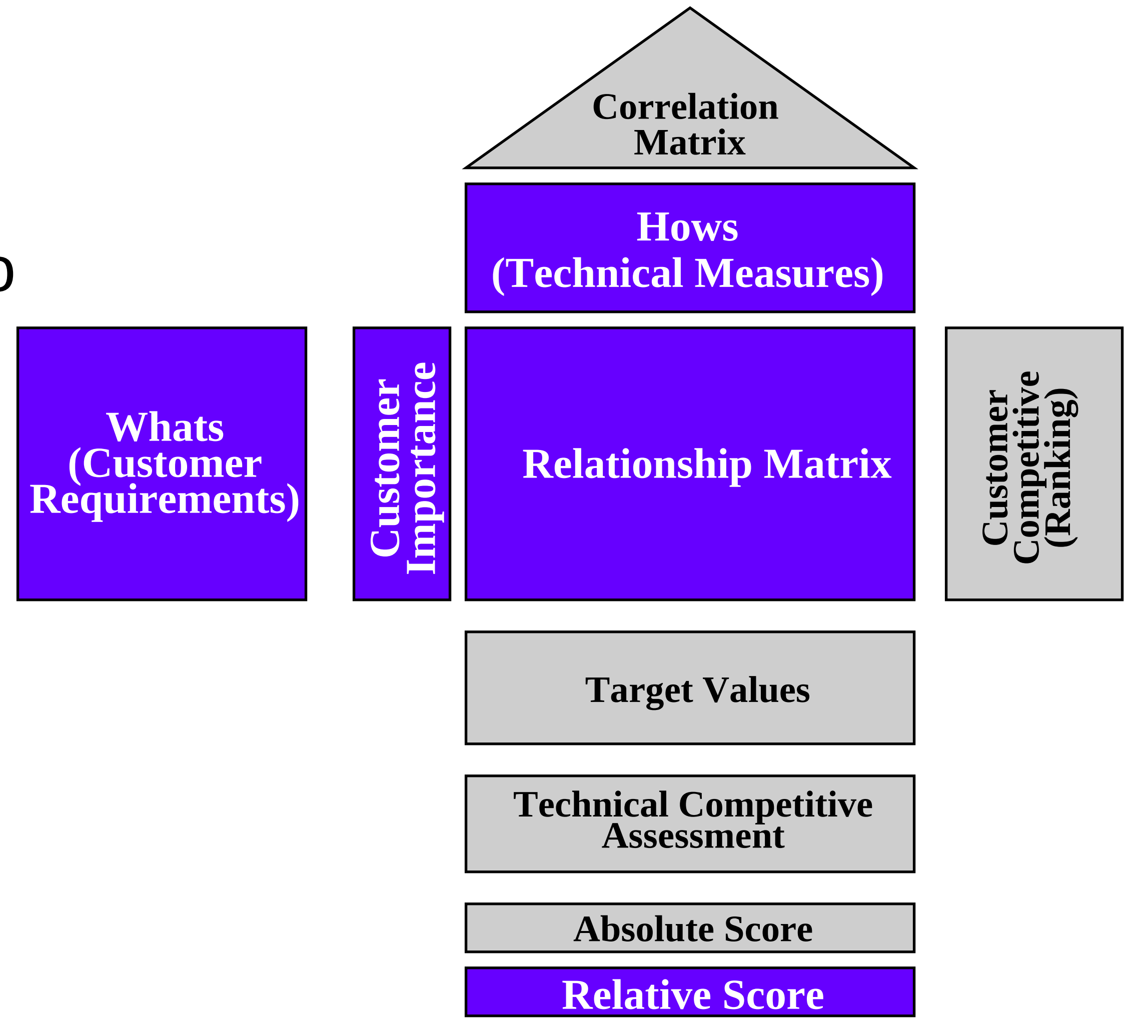
Overview of QFD Process

- QFD abbreviation for "Quality Functional Deployment"
- Originally developed to help organizations focus on customer requirements when developing new products
- Enables multidisciplinary groups to relate the "Whats" to the "Hows"



Step 2, Pt 1: State Change Effectiveness

		Max. Speed	Range	Landing Dist.	Take-off Dist.	Manueverability	Others	State Change Effectivness
Physical State Change	Span	5	4	4	4	3	...	4
	AR	3	4	3	3	2	...	3
	Λ	5	3	5	5	4	...	4
	λ	1	2	1	1	1	...	1
	t/c	1	2	1	1	1	...	1
	Camber	2	2	5	5	5	...	4

- Parameter values range from 1 (little effect) to 5 (large effect)
- Average effect each variable has on performance parameters used as multiplier for rest of matrix
- State changes and performance parameters determined by application, mission, and vehicle

Step 2, Pt 2: Morphing Capability Score

- Morphing methods and materials assigned values (0,1,3, or 9) based on effect on state change
- Final capability score includes technologies employed to reach morphing capability
- Sum of method and technology scores normalized to maximum possible score for vehicle
  - Total morphing score divided by 9 x non-zero elements in matrix
- Aircraft #2, with its hingeless leading and trailing edge control surfaces, leads to higher morphing capability score (1.1 versus 0.8 for Aircraft #1)

Example Capability Score Calculation

		State Change Effectivness	Morphing Methods						Materials and Technologies		
			Pinned Wing Sweep	*Product*	Telescoping	Folding	Hingeless Control Surfaces	Other Morphing Concepts	Smart Materials	Smart Actuators	Other Technologies
Physical State Change	Span	4	3	*12*	0	0	0	0	1	1	…
	AR	3	3	*9*	0	0	0	0	1	1	…
	Λ	4	9	*36*	0	0	0	0	1	1	…
	λ	1	0	*0*	0	0	0	0	0	0	…
	t/c	1	0	*0*	0	0	0	0	0	0	…
	Camber	4	0	*0*	0	0	9	0	1	1	…
			SUM	57	0	0	36	0	15	15	…

Σ (Effectiveness x Methods) = 123

9 x non-zero elements = ÷ 108

Capability Score 1.1

Final capability score normalized to maximum technology value employed to achieve morphing

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Step 2, Pt 3: Morphing Risk Assessment

Aircraft #1

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Folding	0	0	0
Conventional Control Surfaces	0	0	0
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Smart Actuators	1	1	1
	5	5	3

Risk Score 1.08

Aircraft #2

	Risks		
	Cost	Complexity	Manufacturing
Pinned Wing Sweep	3	3	1
Telescoping	0	0	0
Conventional Control Surfaces	0	0	0
Hingeless Control Surfaces	3	9	3
Other Morphing Concepts	0	0	0
Smart Materials	1	1	1
Other Technologies	1	1	1
	8	14	6

Risk Score 2.33

- Risk separated from morphing capability assessment
  - Aids in identification of high risk / high payoff concepts
  - Including with morphing capability determination potentially excludes riskier concepts

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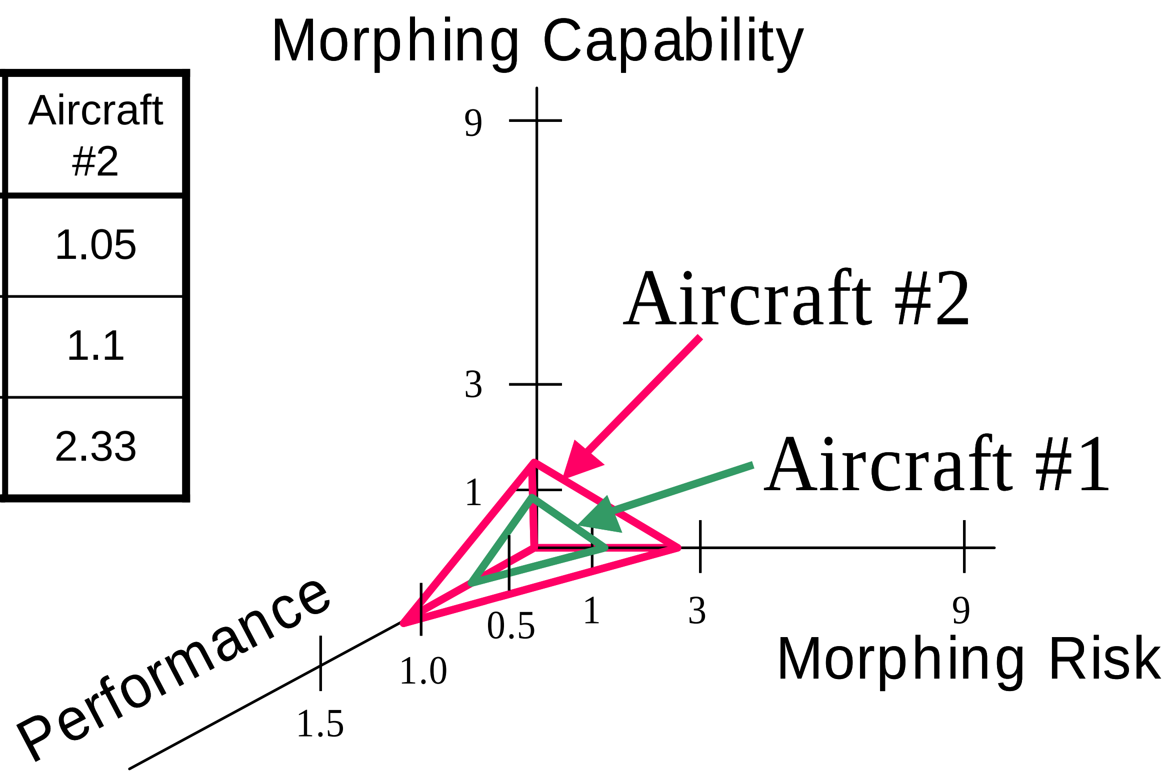
Step 3 – Morphing Capability Index

- Combination of mission impact, morphing capability and morphing risk plotted on individual axes`

	Aircraft #1	Aircraft #2
Mission Impact Score	0.93	1.05
Morphing Capability Score	0.8	1.1
Morphing Risk Score	1.08	2.33



Morphing Concept Development Levels (MCDL)

- MCoA tool provides ability to assess proposed vehicle and technology concepts relative to achieving desired mission capabilities
- MCDL chart provides an embodiment to a broader, qualitative view of morphing capabilities *and* goals for future vehicle systems
  - must present progression of key attributes to a final set of desired features based on the morphing vehicle system objectives—set *a priori* as a reflection of a long-term vision on morphing development
  - should serve as a program-planning tool to indicate general directions and goals for technology and vehicle system morphing capability advancement

What you see here is a preliminary proposed morphing goals that still require further refinement.
Focus is on Air Vehicles.

Vehicle System Attributes in MCDL

- Grouped in two sets of features:
  - Vehicle-type independent
  - Vehicle-specific
- Ranging from no special feature to a full morphing realization
- Features are arranged in streams (columns) and subdivided in ten levels

Preliminary MCDL Chart

Level	Vehicle-independent Features: Mission Effectiveness	Vehicle-independent Features: State Change/Efficiency	Vehicle-independent Features: Adaptability to Environment and/or Threat	Vehicle-independent Features: Generalized Cost ($, weight, complexity, power, reliability)	Vehicle-specific Features: Lift Generation Surfaces	Vehicle-specific Features: Maneuvering Capability	Vehicle-specific Features: Survivability/Maintainability
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat-cannot be done with other methods	Great improvement over existing methods - from component to system levels	Conformally deployed lifting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability/maintainability on demand
9	Enable new mission with improved effectiveness	Large state change - competes with existing methods	Great adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level			Self-healing systems
8	Enable new mission	Large state change - inefficiently replaces existing methods	Great adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the weapon system level		Conformal ... control surfaces from wing-fuselage	
7	Combining (dissimilar) existing missions with superior effectiveness	Moderate state change - exceeds performance of existing methods	Moderate adaptability to environment and/or threat-cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon system level			
6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
5	Combining (dissimilar) existing missions inefficiently	Moderate state change - inefficiently replaces existing methods	Moderate adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the vehicle level	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Aircraf re-trimming after failure/damage, store/load changes, etc.
4	Perform existing missions with superior effectiveness	Minimal state change - exceeds performance of existing methods	Minimal adaptability to environment and/or threat-cannot be done with other methods	Inneficient w.r.t. existing methods - at the vehicle level	Conformal lifting surfaces sweep and/or surface area change	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw	Vehicle real-time reconfigurable flight envelop based on usage and health monitoring information
3	Perform existing missions with improved effectiveness	Minimal state change - competes with existing methods	Provides minimal adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the component level	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes for secondary flight controls; increase maneuverability and decrease vulnerability	In-flight active loads re-distribution
2	Perform existing missions with current effectiveness	Minimal state change - inefficiently replaces existing methods	Provides minimal adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the component level	Discrete lifting surface sweep and/or area change	Conformal lifting surface changes driven by discrete surfaces	Vehicle usage and health monitoring
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat-inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features	No special features

Vehicle-independent Features

Vehicle-specific Features

Morphing levels (from 1 to 10)

Preliminary MCDL Chart

Level	Vehicle-independent Features				Vehicle-specific Features		
Level	Mission Effectiveness	State Change/Efficiency	Adaptability to Environment and/or Threat	Generalized Cost ($, weight, complexity, power, reliability)	Lift Generation Surfaces	Maneuvering Capability	Survivability/Maintainability
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat-cannot be done with other methods	Great improvement over existing methods - from component to system levels	Conformally deployed lifting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability/maintainability on demand
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8	Enable new mission	Large state change - inefficiently replaces existing methods	Great adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the weapon system level		Conformally deployed control surfaces from wing-fuselage	
7	Combining (dissimilar) existing missions with superior effectiveness	Moderate state change - exceeds performance of existing methods	Moderate adaptability to environment and/or threat-cannot be done with other methods	Inneficient w.r.t. existing methods - at the weapon system level			
6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat-exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
5	Combining (dissimilar) existing missions inefficiently	Moderate state change - inefficiently replaces existing methods	Moderate adaptability to environment and/or threat-competes with existing methods	Competes with existing methods - at the vehicle level	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Aircraf re-trimming after failure/damage, store/load changes, etc.
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1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat-inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features	No special features

From minimal features ...

... to a full morphing realization

Vehicle-independent Features

- Describe desired vehicle characteristics independent of its operational environment (i.e., air, water, land, space, or some combination of them)
- Four current “streams”
  - Mission effectiveness: captures the desire to perform existing missions and combinations of existing missions, as well as to enable new missions
  - Adaptability to the environment and threats
  - State change: since focus to achieve these features is through state changes, morphing development should progress in such a way to eventually lead to large state changes
  - Overall cost assessment of the methods employed in the morphing realization, from component to the system level, must be such that it provides great improvements over existing methods

	Vehicle-independent Features			
Level	**Mission Effectiveness**	**State Change/Efficiency**	**Adaptability to Environment and/or Threat**	**Generalized Cost ($, weight, complexity, power, reliability)**
10	Enable new missions with superior effectiveness	Large state change - exceeds performance of existing methods	Great adaptability to environment and/or threat- cannot be done with other methods	Great improvement over existing methods - from component to system levels
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3	Perform existing missions with improved effectiveness	Minimal state change - competes with existing methods	Provides minimal adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the component level
2	Perform existing missions with current effectiveness	Minimal state change - inefficiently replaces existing methods	Provides minimal adaptability to environment and/or threat- competes with existing methods	Competes with existing methods - at the component level
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level

Vehicle-specific Features

- Much more complex to establish
- Based on identification of key features that characterize the vehicle class (i.e., operational media) to be considered
  - Once such characteristics are defined, envisioned phases of development ranging from those requiring no special features to those required for a complete morphing vehicle must be developed for each of those key features
- Proposed MCDL based on three specific features for air vehicles
  - lift generation surfaces
  - means of maneuvering (represented in the chart under the column “Maneuvering Capability”)
  - survivability/ maintainability, particularly during flight operations

	Vehicle-specific Features		
Level	Lift Generation Surfaces	Maneuvering Capability	Survivability/Maintainability
10	Conformally deployed lifting surfaces on demand	High-bandwidth maneuver forces and moments on demand	Adaptability/maintainability on demand
9			Self-healing systems
8		Conformally deployed control surfaces from wing-fuselage	
7			
6	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
5	High- to short-aspect ratio conformal lifting surface change (and vice-versa)	High bandwidth large scale lifting surfaces shape changes for flight control in multiple axes	Aircraf re-trimming after failure/damage, store/load changes, etc.
4	Conformal lifting surfaces sweep and/or surface area change	High bandwidth lifting surface shape changes for primary flight control in roll and pitch axes, secondary in yaw	Vehicle real-time reconfigurable flight envelop based on usage and health monitoring information
3	Local (camber, thickness) airfoil shape changes	Conformal lifting surface changes for secondary flight controls; increase maneuverability and decrease vulnerability	In-flight active loads re-distribution
2	Discrete lifting surface sweep and/or area change	Conformal lifting surface changes driven by discrete surfaces	Vehicle usage and health monitoring
1	Conventional fixed surfaces	No special features	No special features

Assumption used to established these:
Inspired in biological systems, the desired morphing aircraft would conformably deploy lifting surfaces, provide high-bandwidth maneuver forces and moments, and present adaptability/ maintainability on demand

Vehicle Features

- **Vehicle-specific Feature** streams help guide the research investment for development of specific features associated with a vehicle being operated in given media
- In contrast, the **Vehicle-independent Features** are what ultimately need to be present in a new system that will satisfy the stated needs

Example: Aircraft #2

Level	Vehicle-independent Features				Vehicle-specific Features		
Level	Mission Effectiveness	State Change/Efficiency	Adaptability to Environment and/or Threat	Generalized Cost ($, weight, complexity, power, reliability)	Lift Generation Surfaces	Maneuvering Capability	Survivability/Maintainability
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9	Enable new mission with improved effectiveness	Large state change - competes with existing methods	Great adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the weapon system level			Self-healing systems
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6	Combining (dissimilar) existing missions with improved effectiveness	Moderate state change - competes with existing methods	Moderate adaptability to environment and/or threat- exceeds performance of existing methods	Great improvement over existing methods - at the vehicle level	Hybrid local and global lifting surface characteristics change		Adaptive reconfiguration integrated with vehicle health management system
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1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features	No special features

Example: Aircraft #2 (cont'd)

- Aircraft #2 program will make progress in the streams indicated in the MCDL in support to morphing objectives
  - such a program, however, will not address certain key features that will be part of a complete morphing aircraft
  - new development programs in those areas will be necessary to attain the complete morphing objectives.
- By representing different programs using this common framework and process, program managers and researchers will see which features are being developed and which ones are lagging and need more attention/support
  - In this example: survivability/maintainability (still level 1 in MCDL)

MCA Summary

- A Morphing Capability Assessment process has been proposed
  - MCDL provides the context for MCA
  - MCoA provides assessment of solutions
- MCoA requires a multi-step process
  - Defined mission is a required element
  - The initial step determines the effect of morphing on the mission
  - The 2nd step uses a modified QFD to score effects of technology and risk on the state (i.e., “morphing”) changes
  - Step 3 relates mission effect to capability score to assess morphing capability
  - Analysis feeds into Morphing Concept Development Level (MCDL)
- MCDL chart contains general morphing vehicle system features and the corresponding envisioned development stages towards a complete morphing vehicle realization
  - Guide and track morphing capability development
  - Could support investment decisions for future R&D programs

Proposed MCA process

Establish broader, long-term S&T goals for morphing vehicle development

Morphing Concept Development Levels (MCDL) chart

	Vehicle-independent Features				Vehicle-specific Features	
Level	Mission Effectiveness	State Change/Efficiency	Adaptability to Environment and/or Threat	Generalized Cost ($, weight, complexity, power, reliability)	Lift Generation Surfaces	Maneuvering Capability
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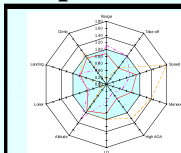
1	Perform existing missions inefficiently	No state change	Provides minimal adaptability to environment and/or threat- inefficiently replaces existing methods	Inneficient w.r.t. existing methods - at the component level	Conventional fixed surfaces	No special features

Given desired mission, assess vehicle concepts/designs

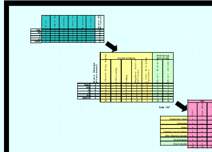
Morphing Concept Assessment (MCoA)

Step 1



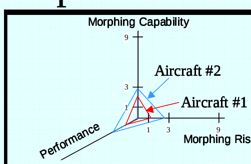
Determine *Mission Impact Score*

Step 2



Evaluate *Morphing Capability Score*

Step 3



Graphically present Morphing Scores

MCA Summary

- A Morphing Capability Assessment process has been proposed
  - MCDL provides the context for MCA
  - MCoA provides assessment of solutions
- MCoA requires a multi-step process
  - Defined mission is a required element
  - The initial step determines the effect of morphing on the mission
  - The 2^{nd} step uses a modified QFD to score effects of technology and risk on the state (i.e., “morphing”) changes
  - Step 3 relates mission effect to capability score to assess morphing capability
  - Analysis feeds into Morphing Concept Development Level (MCDL)
- MCDL chart contains general morphing vehicle system features and the corresponding envisioned development stages towards a complete morphing vehicle realization
  - Guide and track morphing capability development
  - Could support investment decisions for future R&D programs

Further MCA development could greatly benefit from the input of this community!

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Future Work

- Determine method to generate morphing mission impact score similar to morphing capability and risk
  - Scale of 1, 3, or 9
- Investigate other numerical analysis procedures instead of mean or weighted mean in the Mission Impact analysis
- MCDL needs further refinements to represent all the key features desired in morphing vehicles
- Apply further test cases
  - F/A-18 vs. AAW F-18
  - More elaborate morphing aircraft designs
  - Other morphing vehicle systems (e.g., morphing ships, combined water-air vehicles)
- Investigate application of MCoA process to other technologies or vehicles (e.g., prognostics, UUV)
  - Process designed to be a general framework
  - QFD techniques and radar plots can be modified to match technologies of interest

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This paper describes a framework and process for assessing (1) vehicle morphing capability in the context of a desired mission scenario, (2) vehicle performance needed to realize the mission, and (3) the state changes and potential technology advancements required to enable that vehicle performance. The process is subdivided into two parts: Morphing Concept Assessment (MCA) and Morphing Concept Development Levels (MCDLs). This process is applied to an air vehicle to illustrate its use. While the paper focuses on air vehicles, the framework is intended to be independent of vehicle operational media (e.g., air, water, land, space). Even though many aspects of the assessment process are subjective, it provides a common framework for identifying, discussing, and evaluating critical vehicle and technology issues. It also provides a foundation for the development of vehicle and technology research and development (R&D) programs.

15. SUBJECT TERMS

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